Mapping Hot Gas in the Universe using the Sunyaev-Zeldovich Effect

Eiichiro Komatsu (Max-Planck-Institut für Astrophysik)
OKC Cosmology and Gravity Seminar, Oskar Klein Centre,
February 15, 2017

This presentation is based primarily upon…

1. **T. Kitayama** et al., "*The Sunyaev-Zeldovich effect at 5": RXJ1347.5–1145 imaged by ALMA*", PASJ, 68, 88 (2016), arXiv:1607.08833 **Data**

2. **K. Dolag**, EK & R.A. Sunyaev, "*SZ effects in the Magneticum Pathfinder Simulation: Comparison with Planck, SPT, and SCT results*", MNRAS, 463, 1797 (2016), arXiv:1509.05134 **Sim**

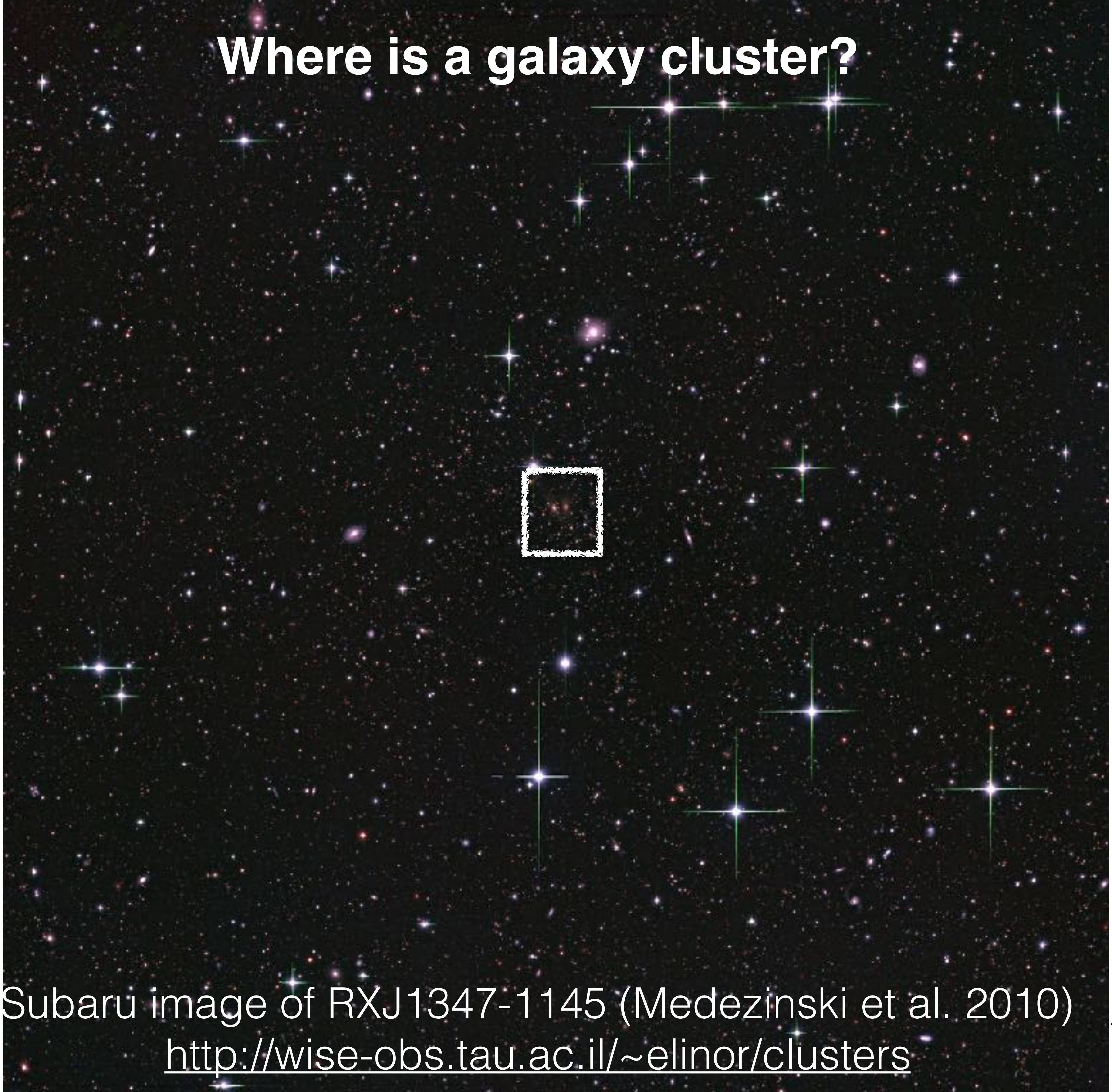
[I probably do not have time to cover this]

3. **X. Shi** & EK, "*Analytical model for non-thermal pressure in galaxy clusters*", MNRAS 442, 521 (2014), arXiv:1401.7657 **Model**

Where is a galaxy cluster?

Subaru image of RXJ1347-1145 (Medezinski et al. 2010)
http://wise-obs.tau.ac.il/~elinor/clusters

Where is a galaxy cluster?



Subaru image of RXJ1347-1145 (Medezinski et al. 2010)
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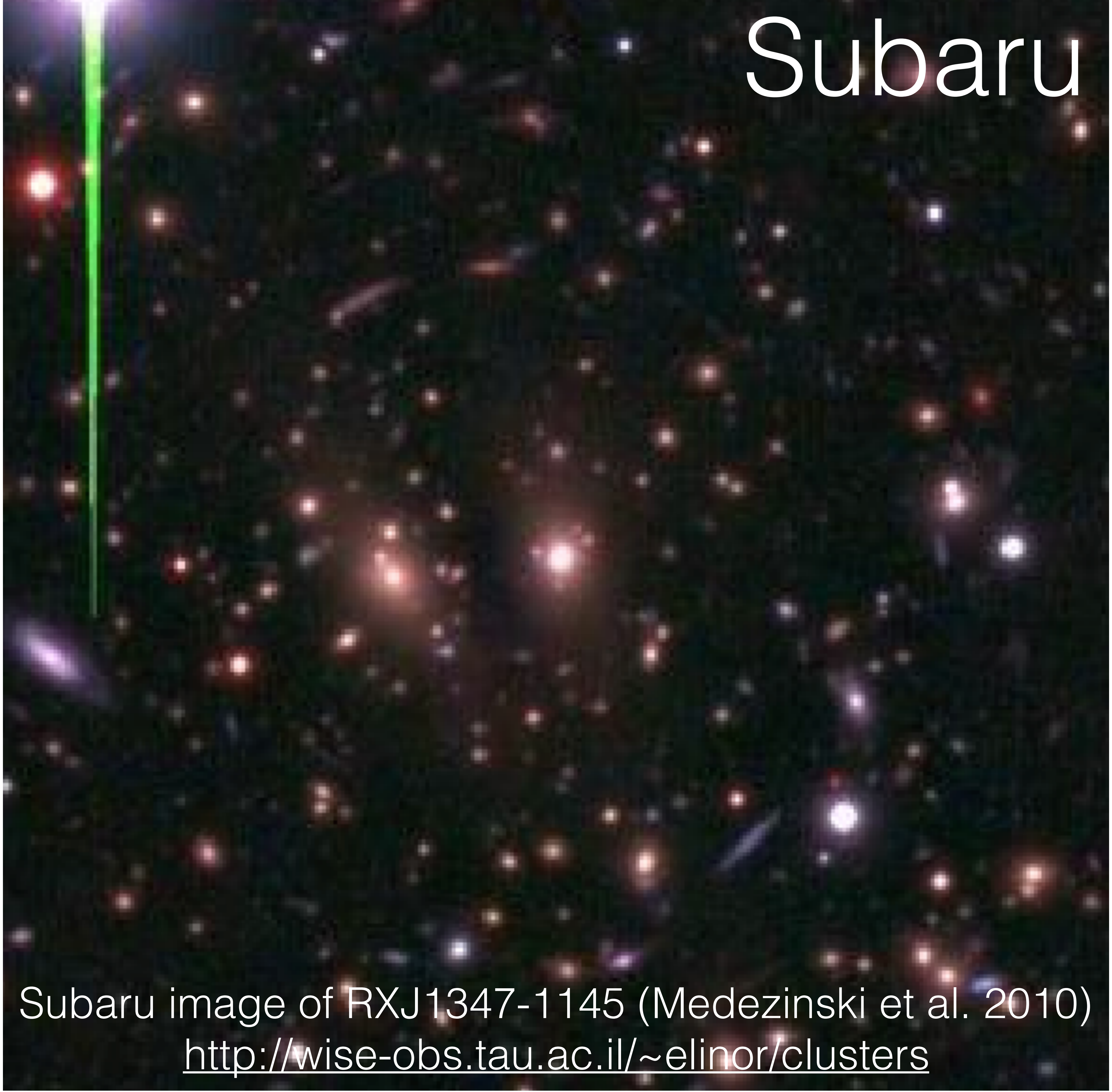
Subaru



Subaru image of RXJ1347-1145 (Medezinski et al. 2010)
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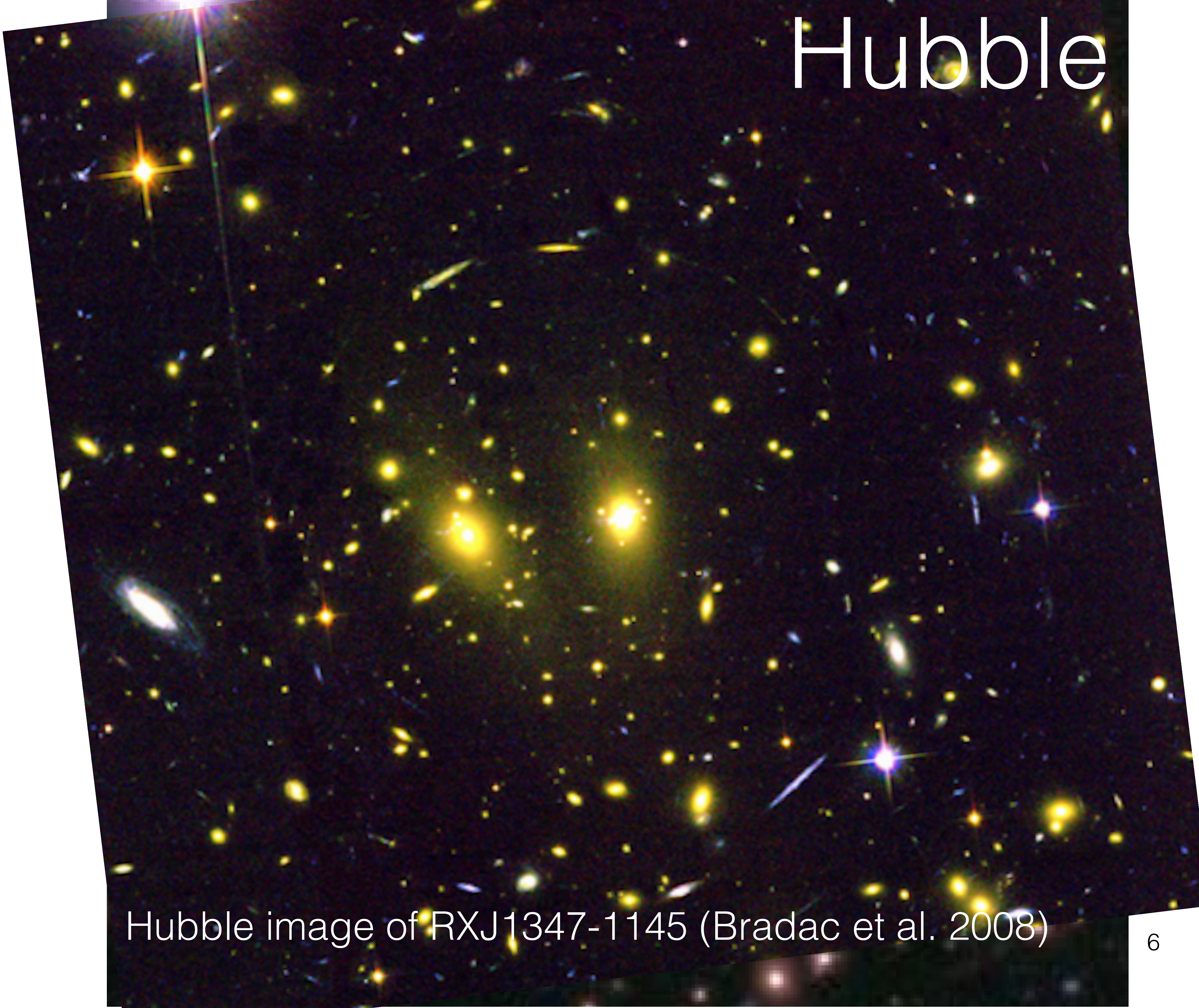
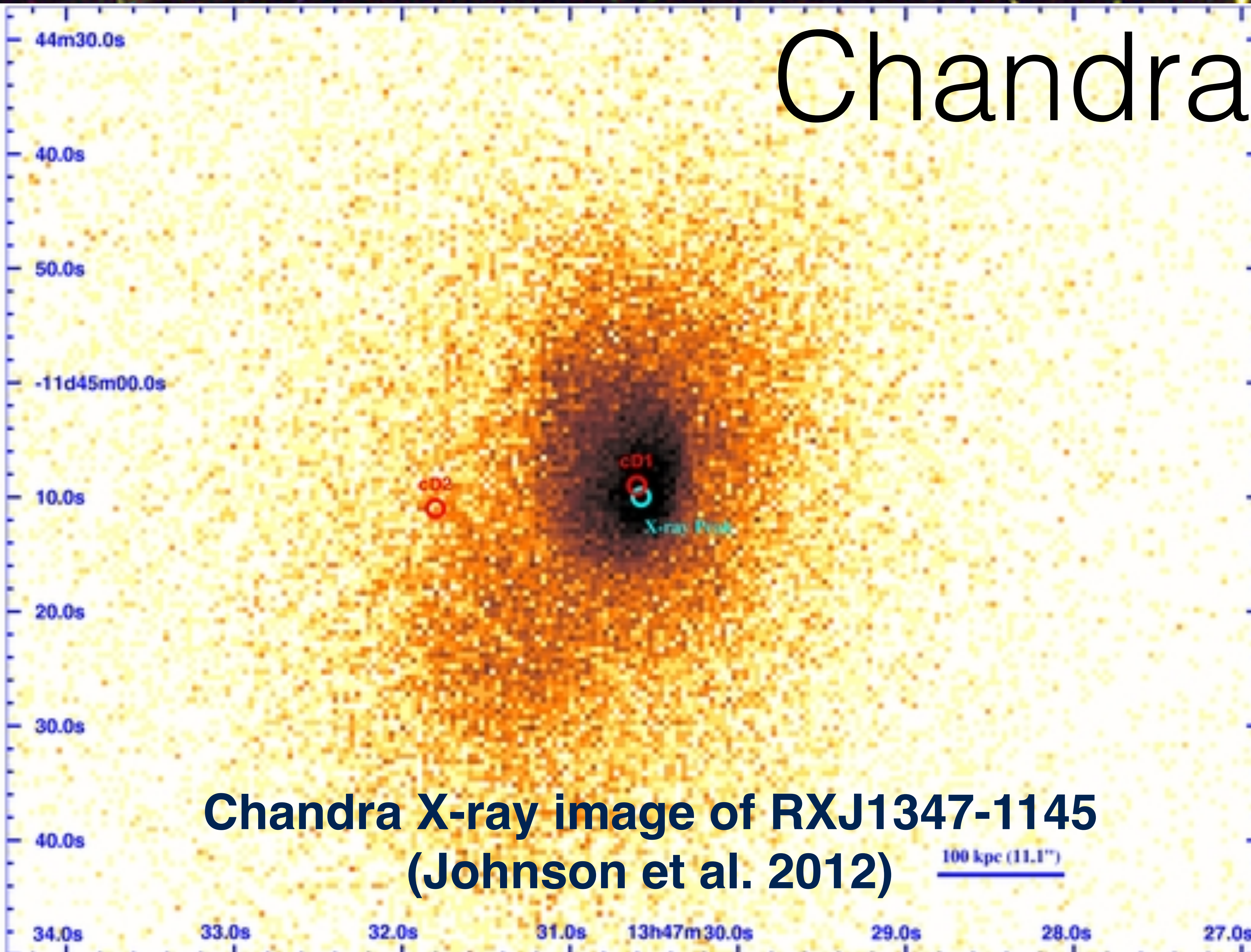
Hubble

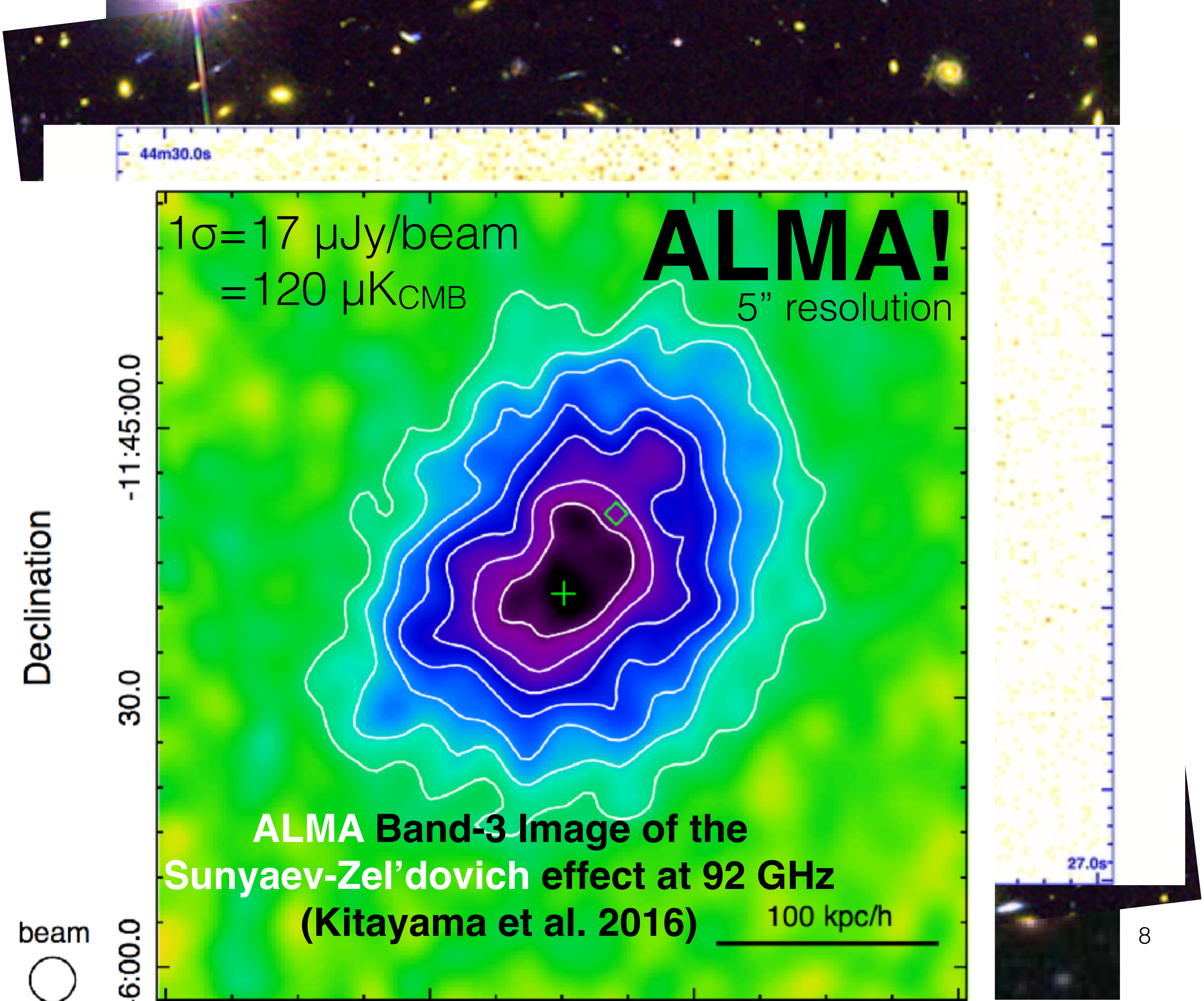


Hubble image of RXJ1347-1145 (Bradac et al. 2008)

Chandra

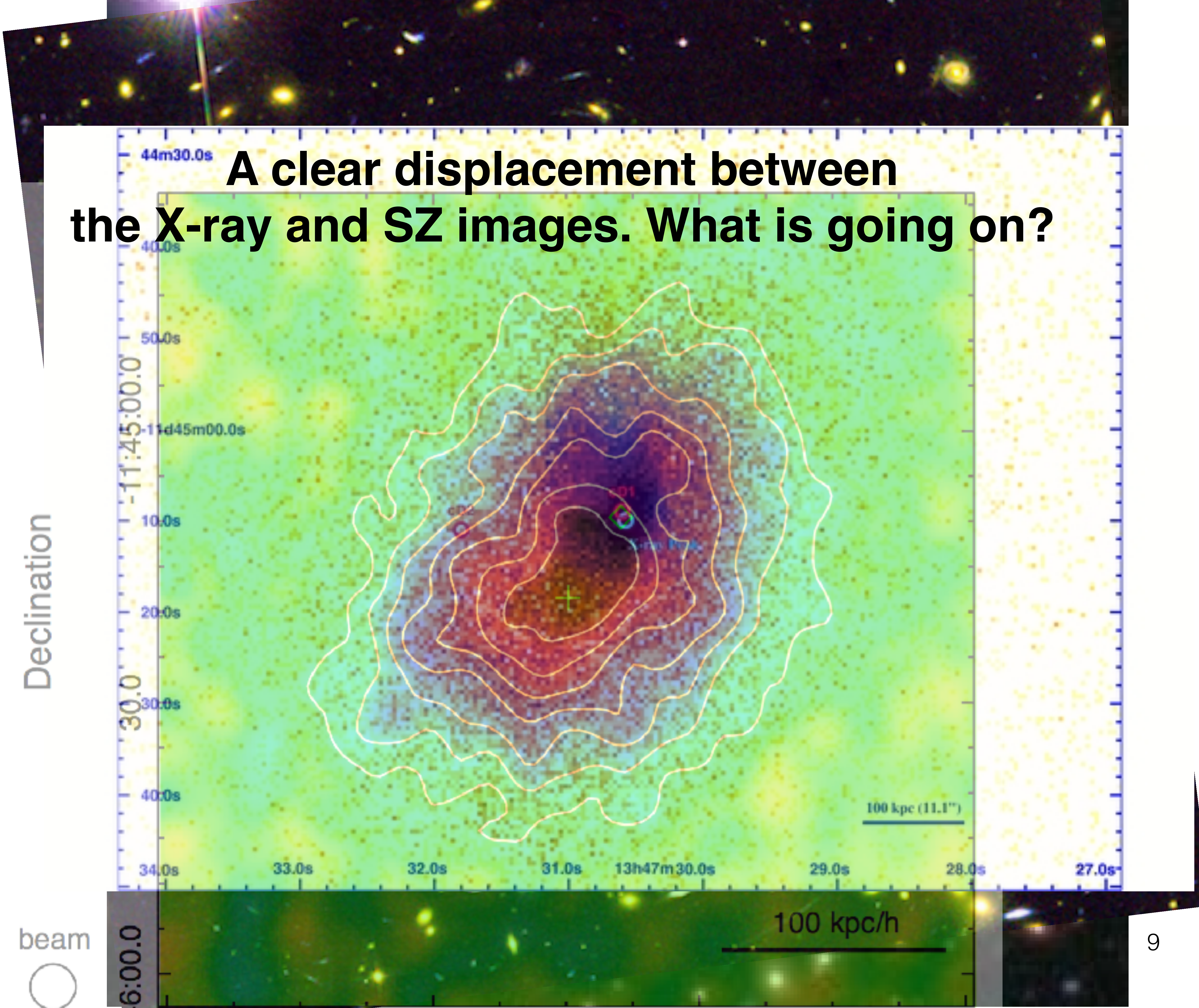


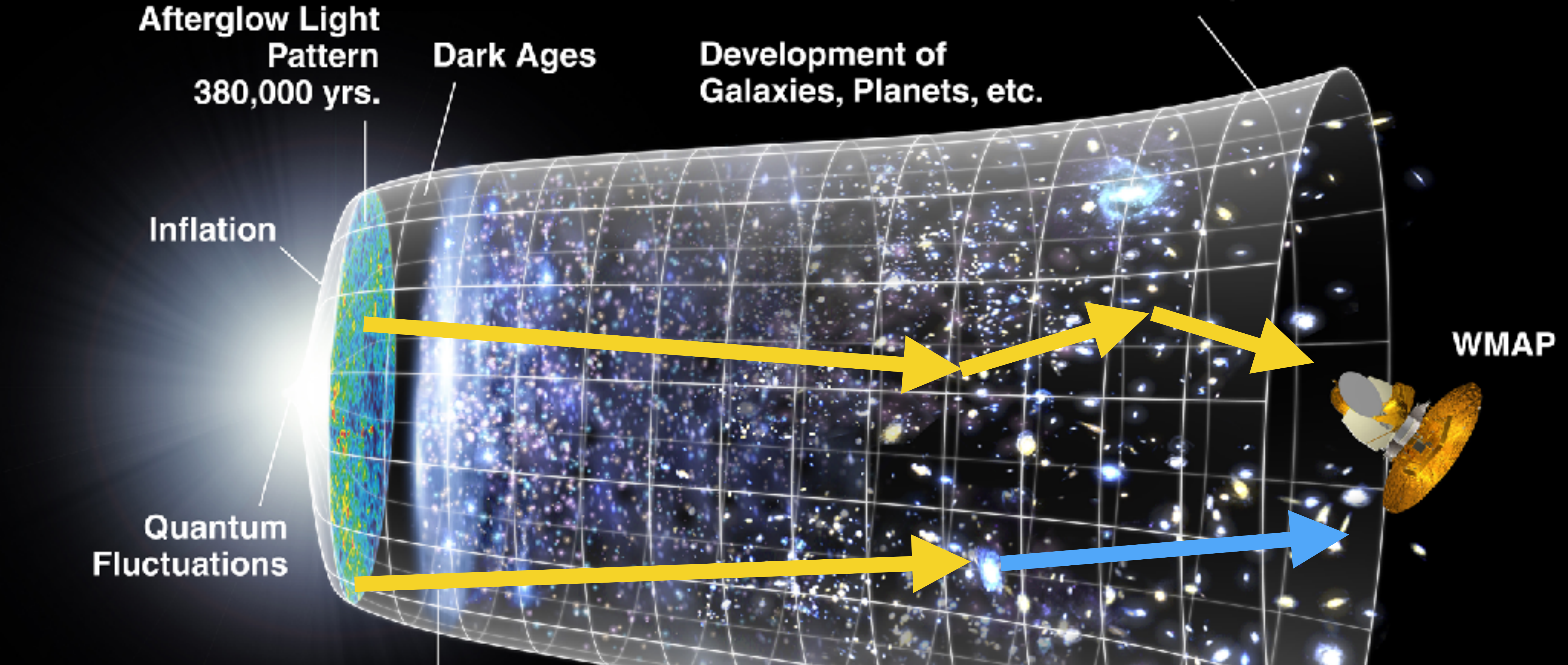
Chandra X-ray image of RXJ1347-1145
(Johnson et al. 2012)

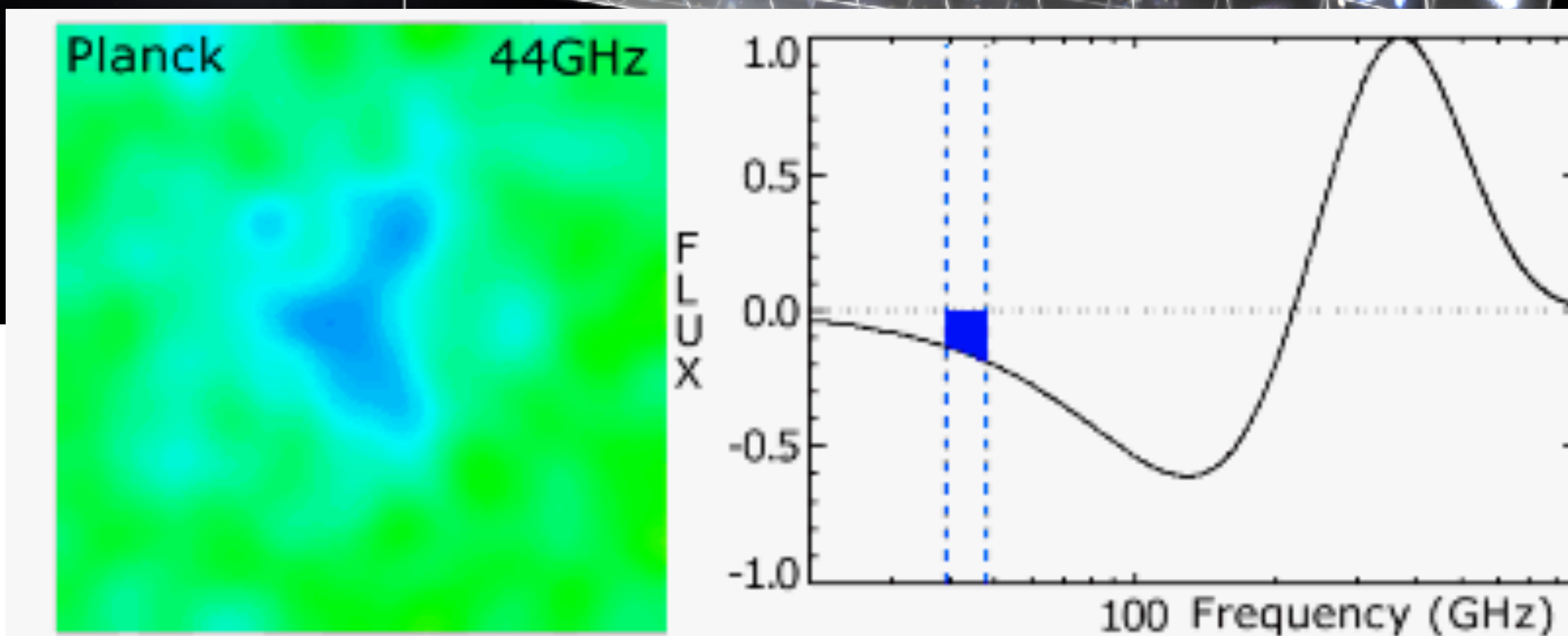


44m30.0s
27.0s
Declination
-11:45:00.0
30.0
6:00.0
beam
1σ=17 μJy/beam
=120 μK CMB
ALMA!
5" resolution
ALMA Band-3 Image of the
Sunyaev-Zel'dovich effect at 92 GHz
(Kitayama et al. 2016)
100 kpc/h

A clear displacement between the X-ray and SZ images. What is going on?

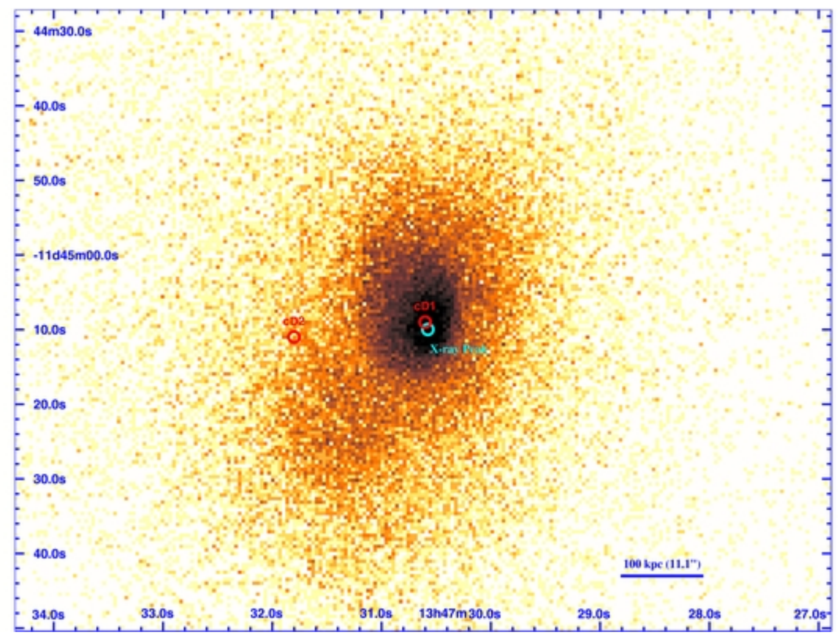


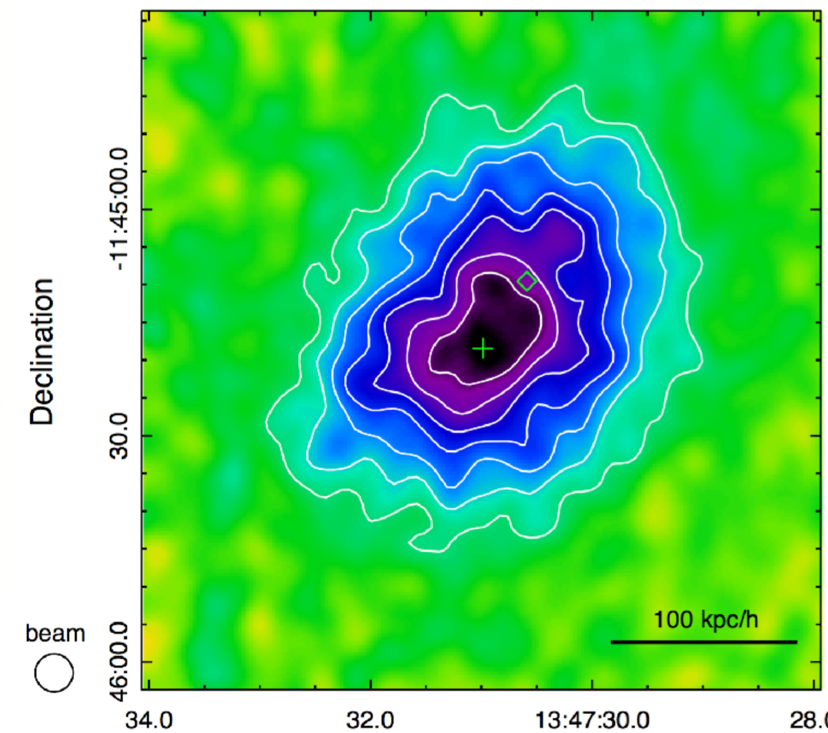

Afterglow Light Pattern 380,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Inflation
Quantum Fluctuations
WMAP


Planck
44GHz
FLUX
1.0
0.5
0.0
-0.5
-1.0
100
Frequency (GHz)

Multi-wavelength Data

$$I_X = \int dl \; n_e^2 \Lambda(T_X) \qquad I_{SZ} = g_\nu \frac{\sigma_T k_B}{m_e c^2} \int dl \; n_e T_e$$





<u>Optical</u>:
- $10^{2\text{–}3}$ galaxies
- velocity dispersion
- gravitational lensing

<u>X-ray</u>:
- hot gas ($10^{7\text{–}8}$ K)
- spectroscopic T_X
- Intensity ~ $n_e^2 L$

<u>SZ</u> [microwave]:
- hot gas ($10^{7\text{-}8}$ K)
- electron pressure
- Intensity ~ $n_e T_e L$

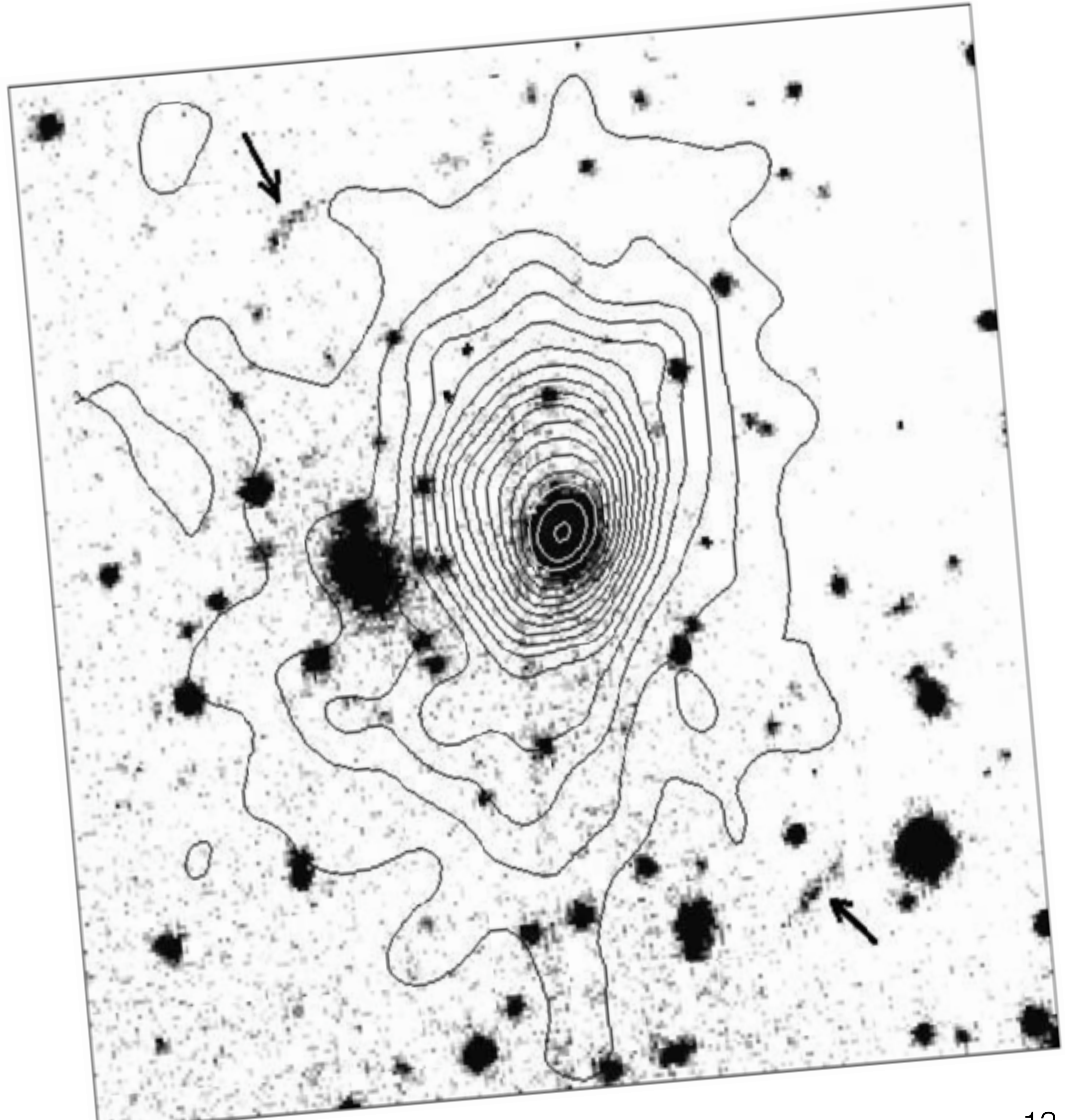
A Story about RXJ1347–1145

- Let me tell you a little story about this particular cluster, which **highlights the unique power of the SZ data to study cluster astrophysics**
  - A massive cluster with 10^{15} M_{sun} at z=0.45
    - *The most X-ray luminous galaxy cluster* found in the ROSAT All Sky Survey
  - Very compact, “cool core” cluster

1997

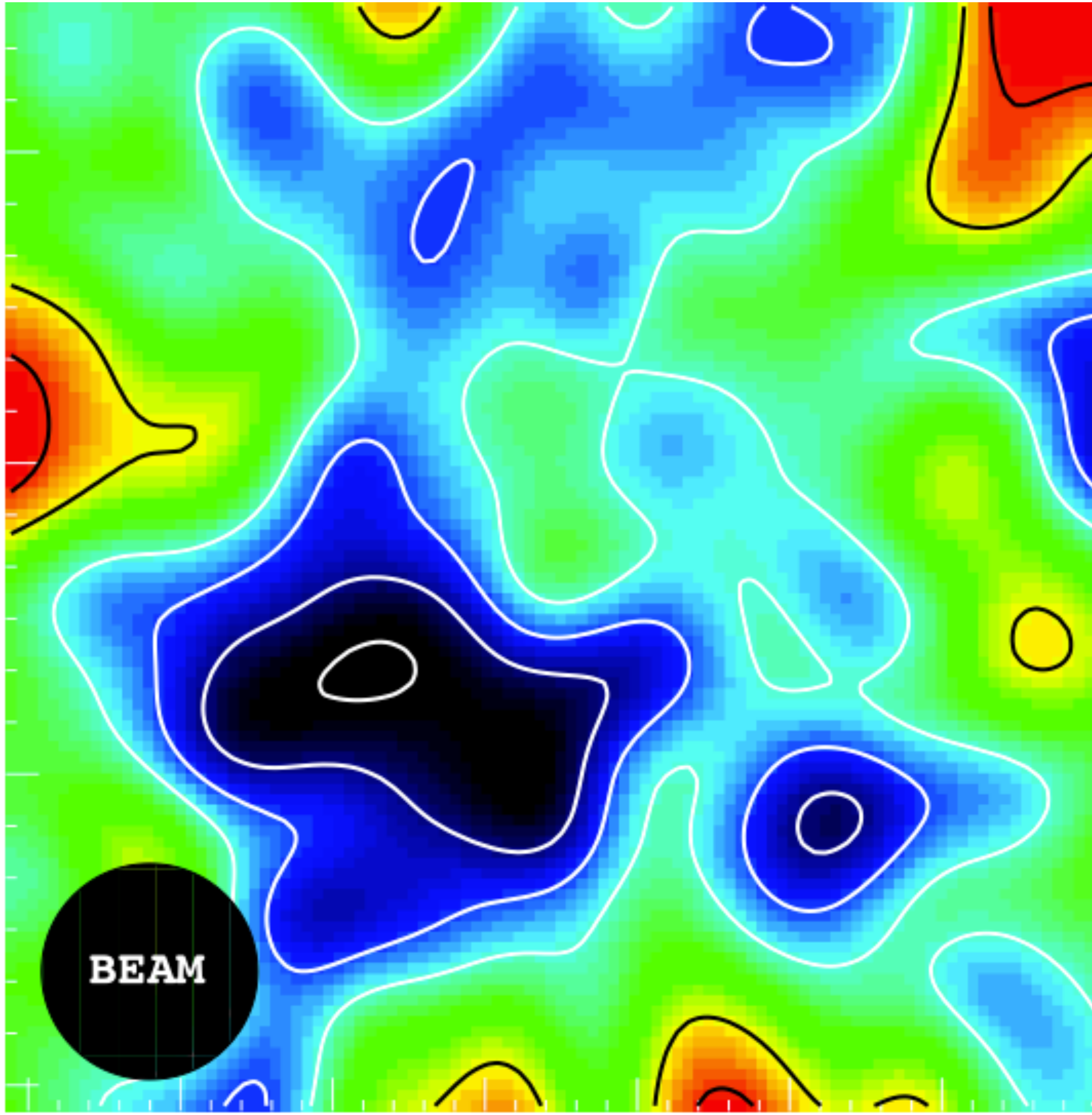
ROSAT/HRI image
[Schindler et al.]
5” resolution

- 0.1–2.4 keV
- Looked pretty “spherical”
- Thought to be a typical, relaxed, cooling-flow cluster



2001

SZ w/ Nobeyama
[Komatsu et al.]
<u>12” resolution</u>



- The highest angular resolution SZ mapping at that time
- (The record holder for a decade)
- **A surprise!**

2001

SZ w/ Nobeyama
[Komatsu et al.]
<u>12” resolution</u>

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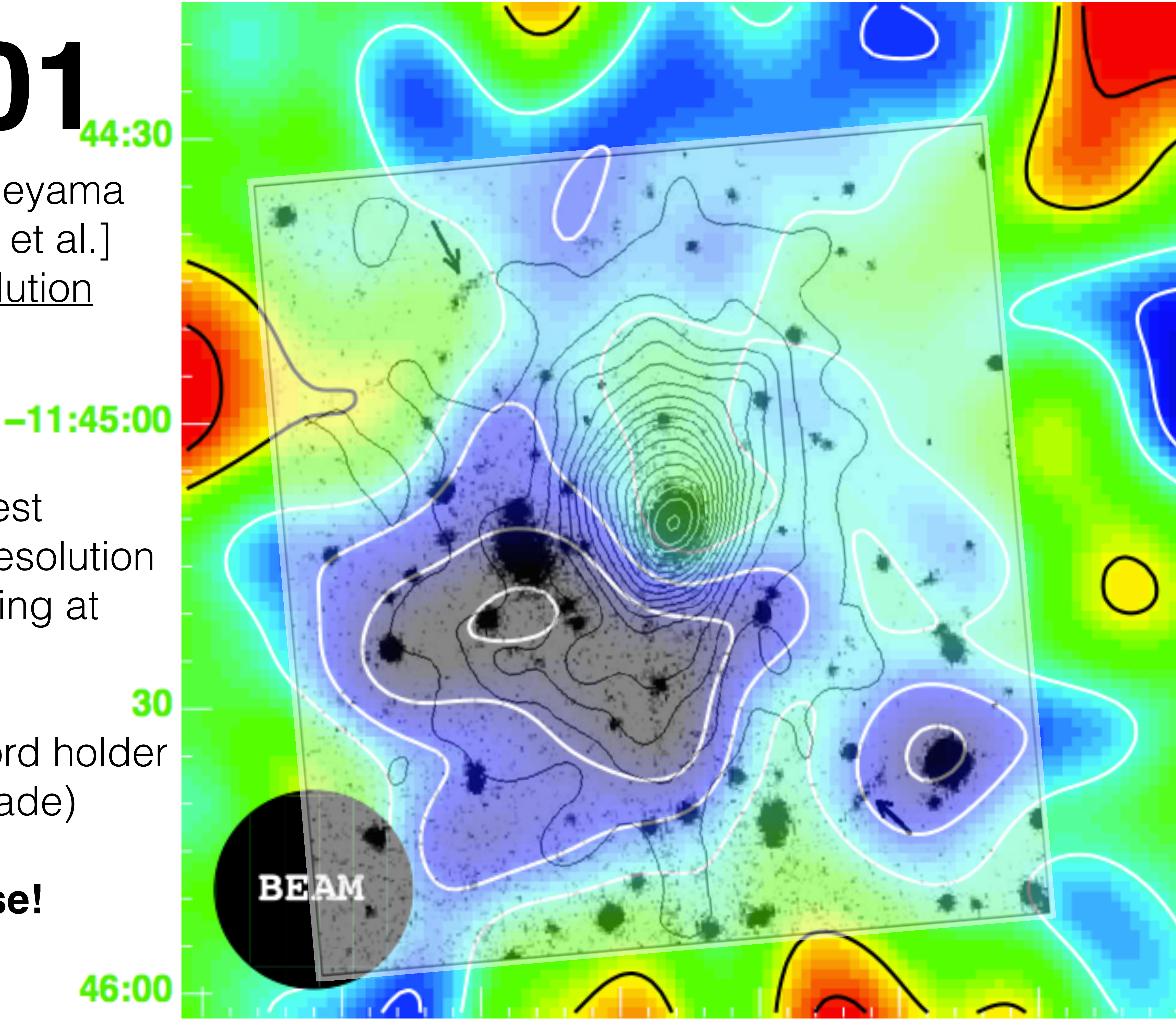
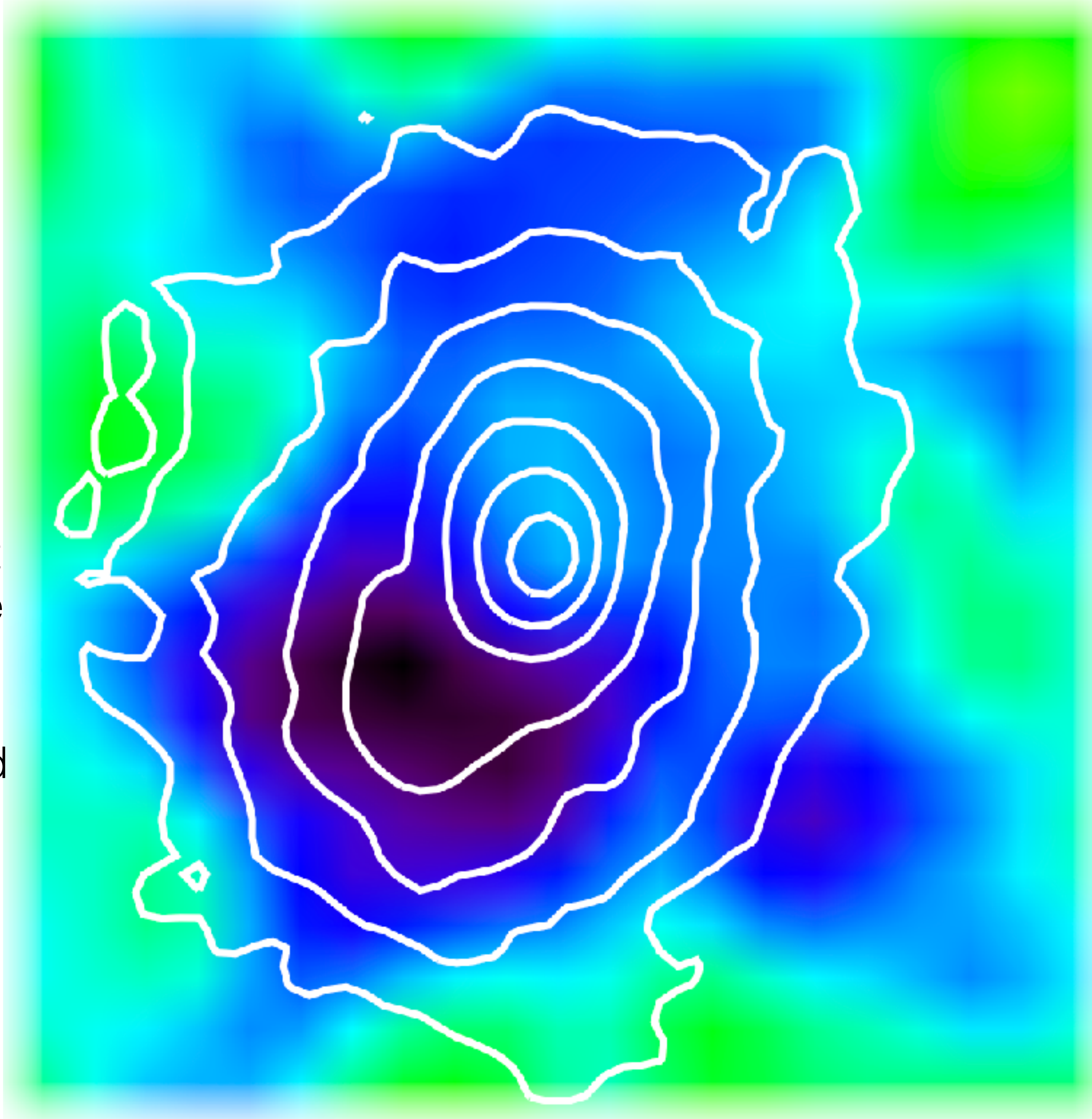


2002

X-ray w/ Chandra
[Allen et al.]

- 0.5–7 keV
- An excess X-ray emission found at the location of the SZ excess
- A hot gas, missed by ROSAT due to the lack of sensitivity at high energies!



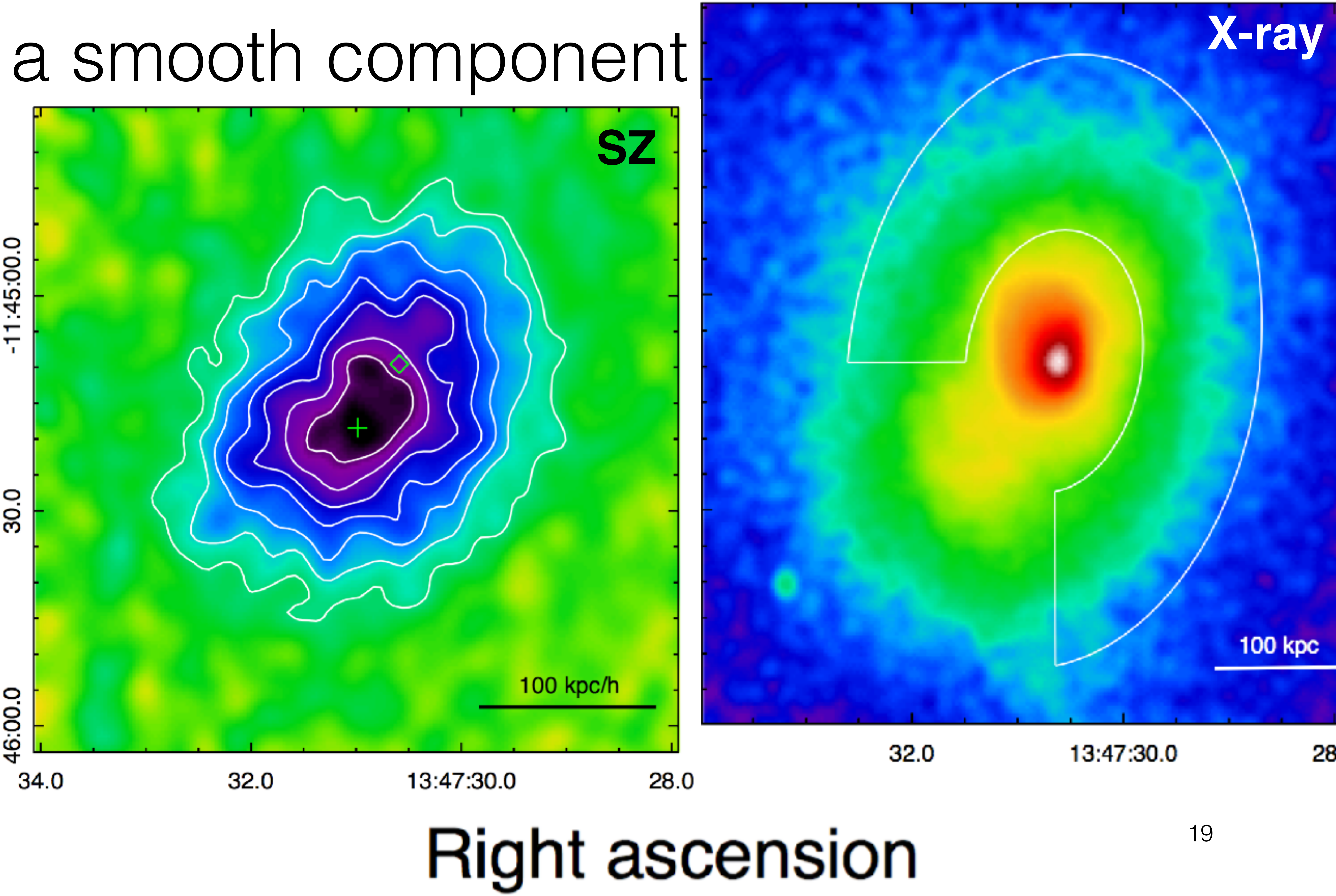
A lesson learned

- X-ray observations are band-limited
  - They are not usually not sensitive to very hot gas with temperature >10(1+z) keV
- SZ observations are **not** band-limited
  - They are in principle sensitive to arbitrarily high temperatures (more precisely, pressure)
- SZ data probe electron pressure: a good probe of shock-heated gas due to mergers
  - *RXJ1347–1145 was thought to be a relaxed cluster. Our Nobeyama data challenged it, and now it is accepted that this cluster is a merging system!*

We have ALMA. Now what?

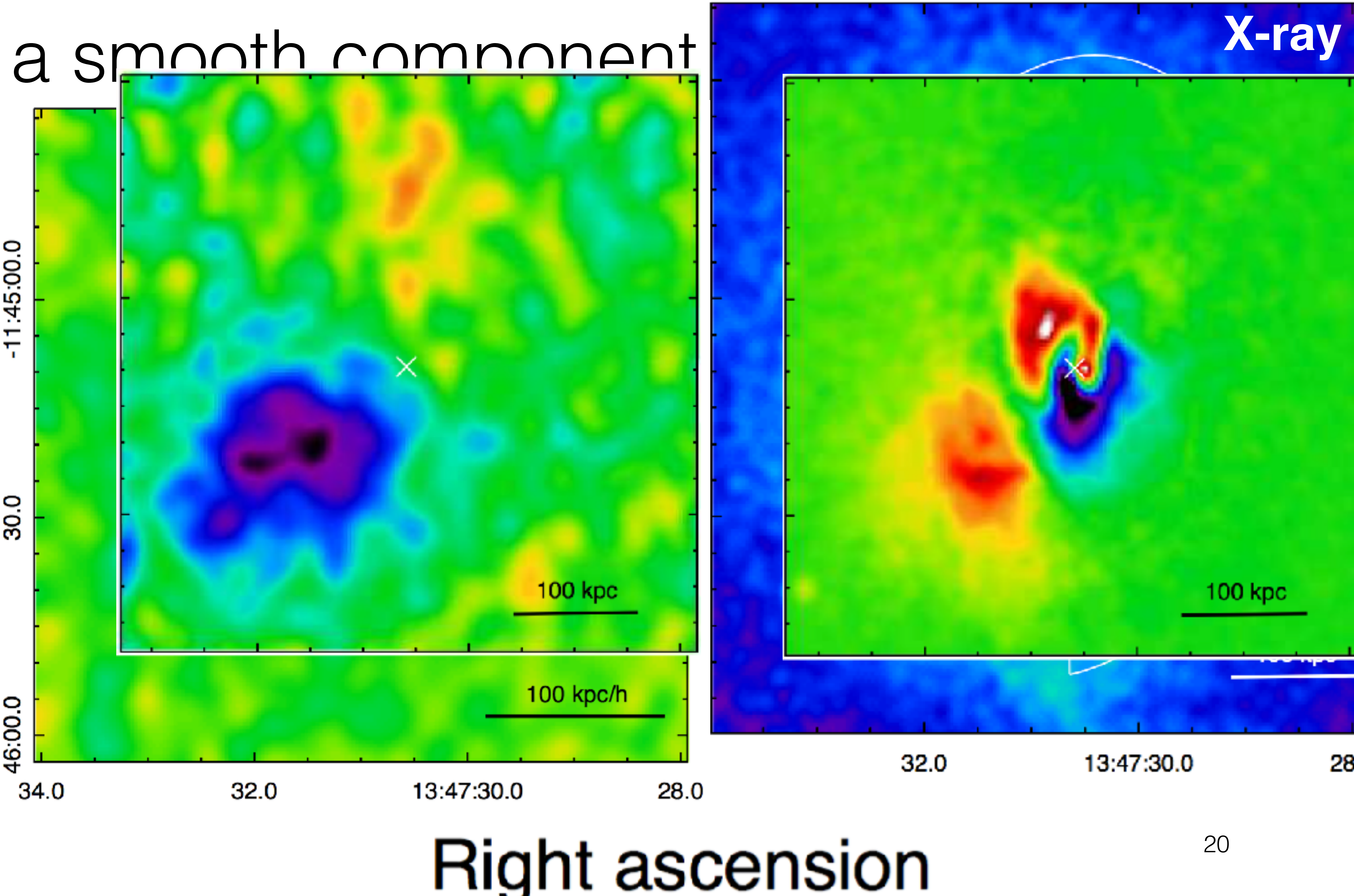
- What is a new science we can do with such high resolution, high sensitivity measurements?
    - Finding shocks and hot clumps is fun, but can we do something new and more quantitative?
- One example: **Pressure fluctuations**

Let's subtract a smooth component



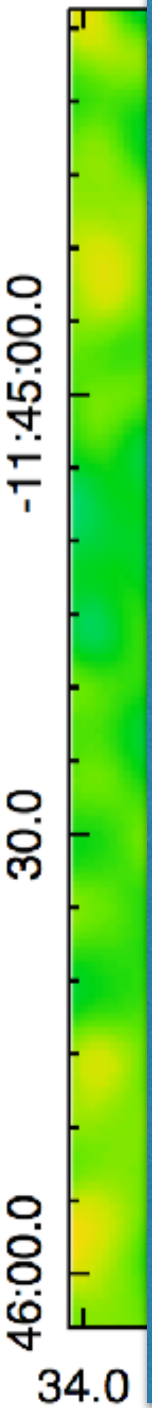
Kitayama et al., in prep

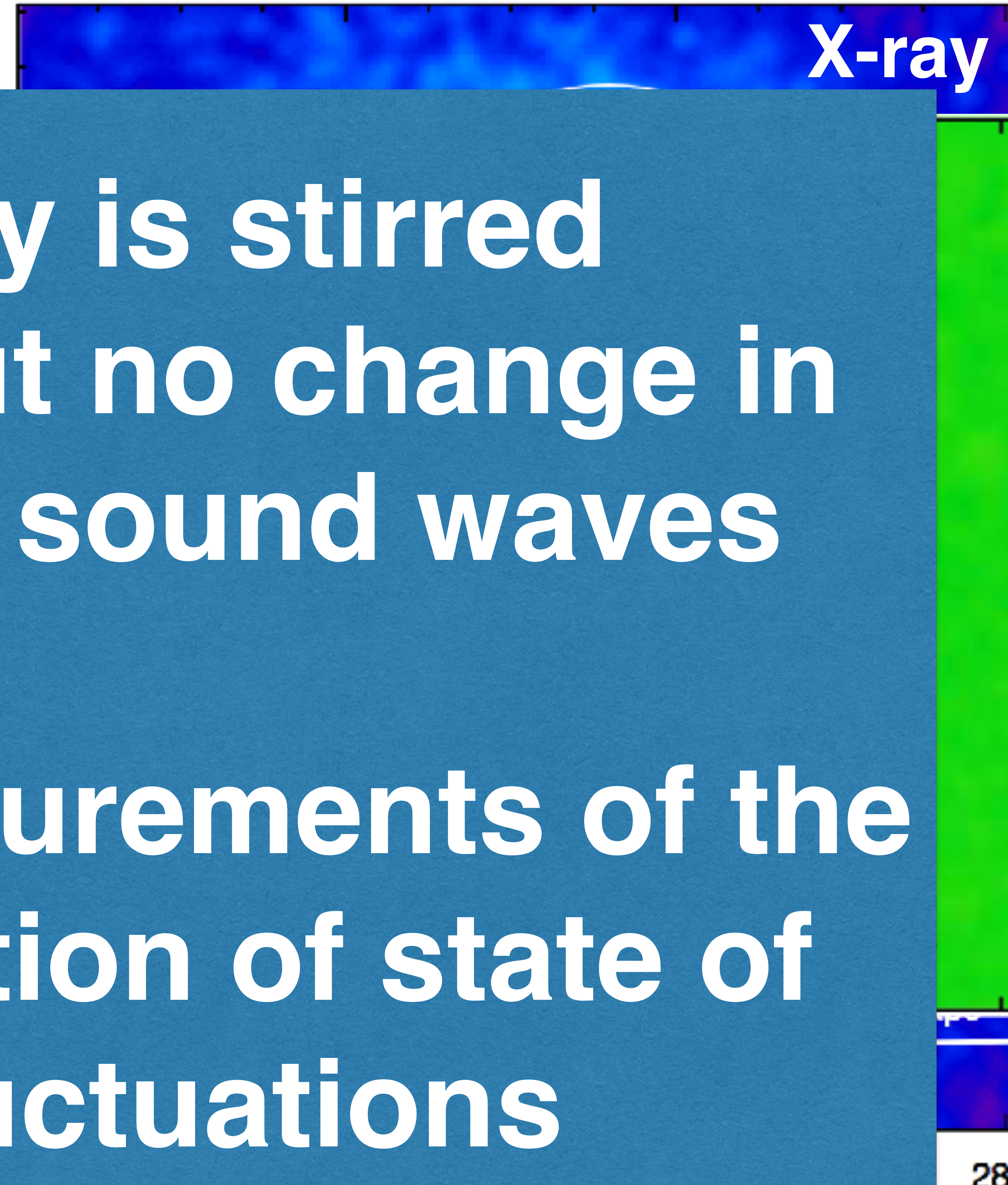
Let's subtract a smooth component



Kitayama et al., in prep

Let's subtract a smooth component



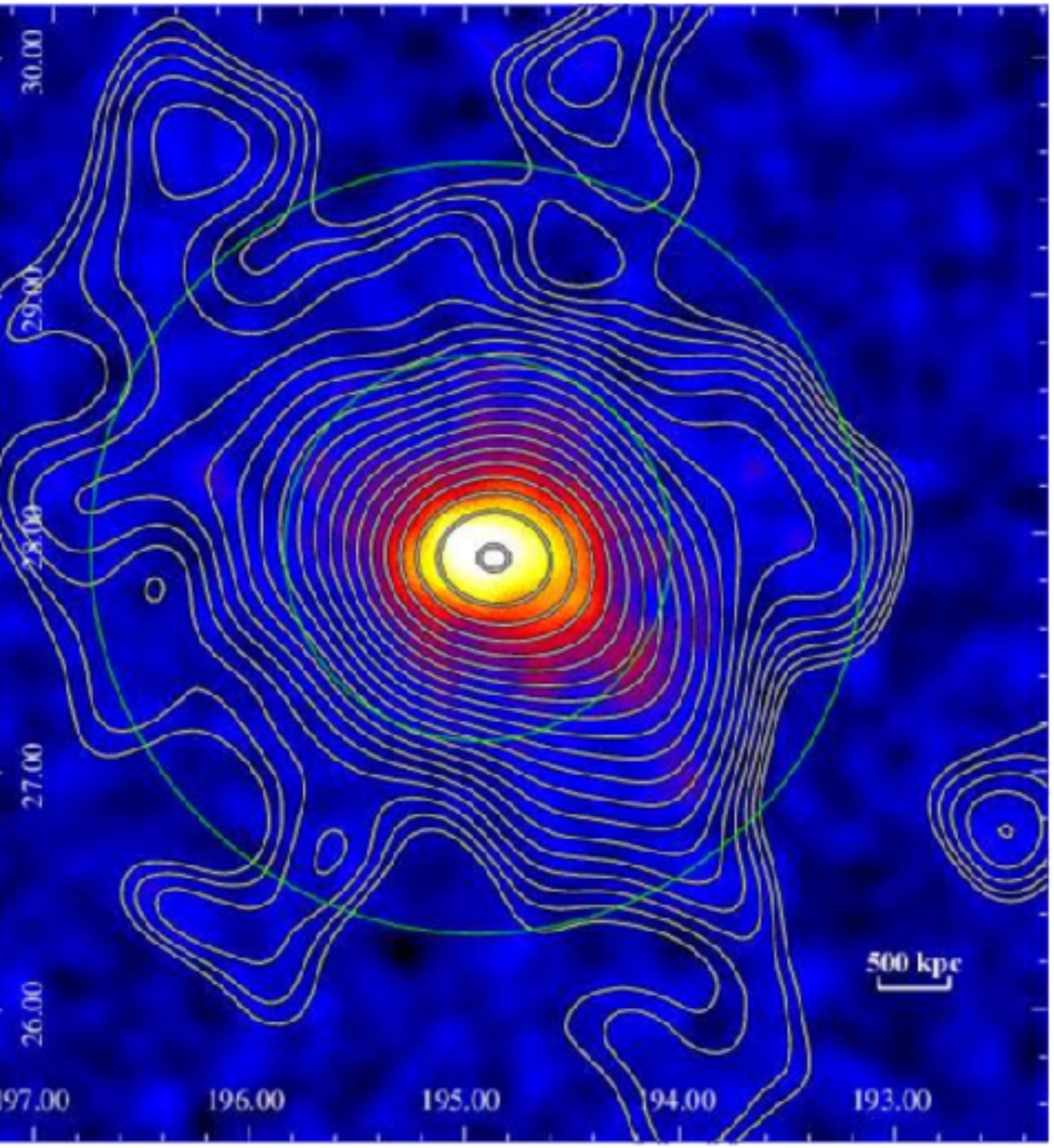


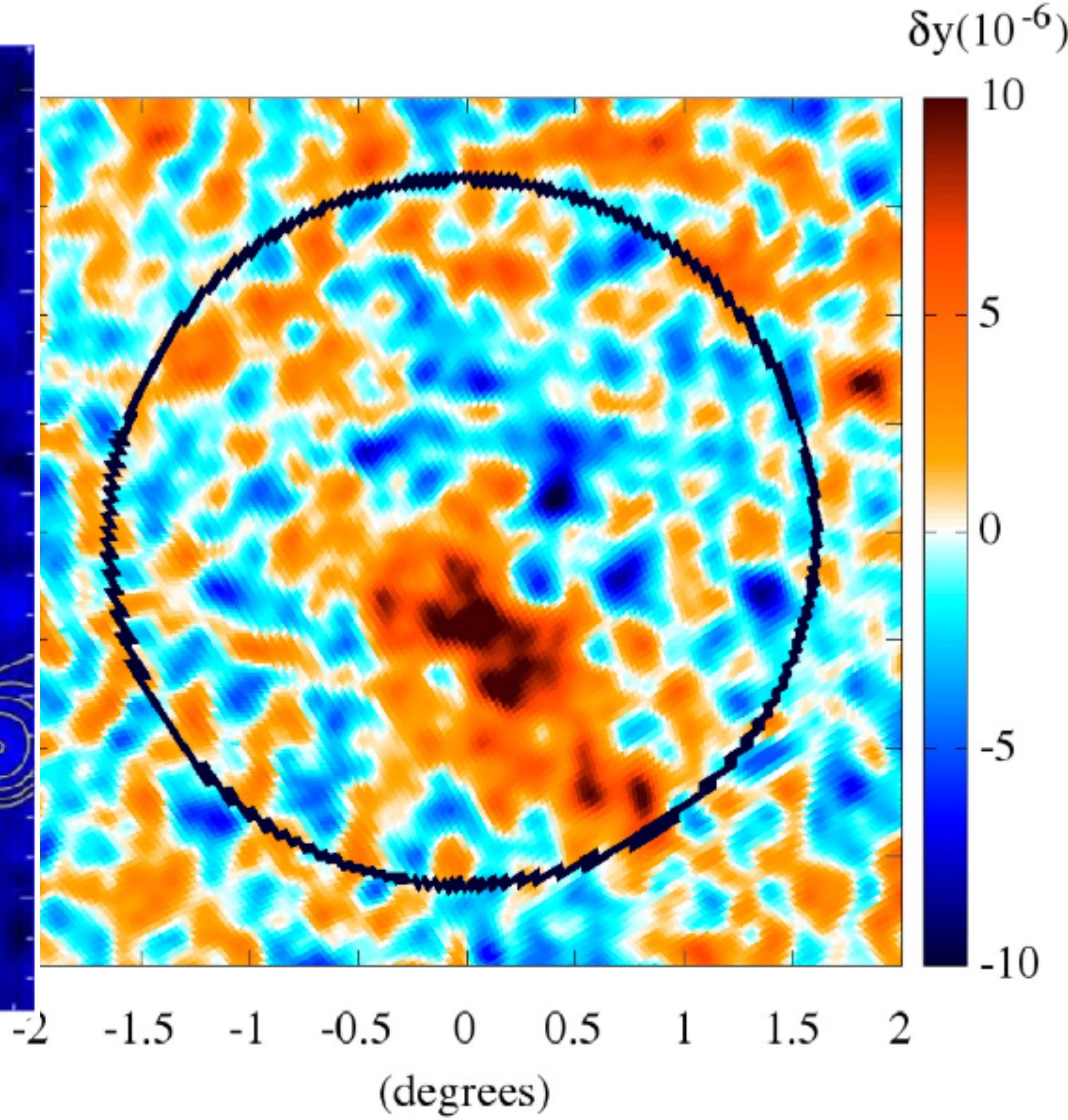
Gas density is stirred ("sloshed"), but no change in pressure! Not sound waves

=> Unique measurements of the effective equation of state of density fluctuations

Right ascension

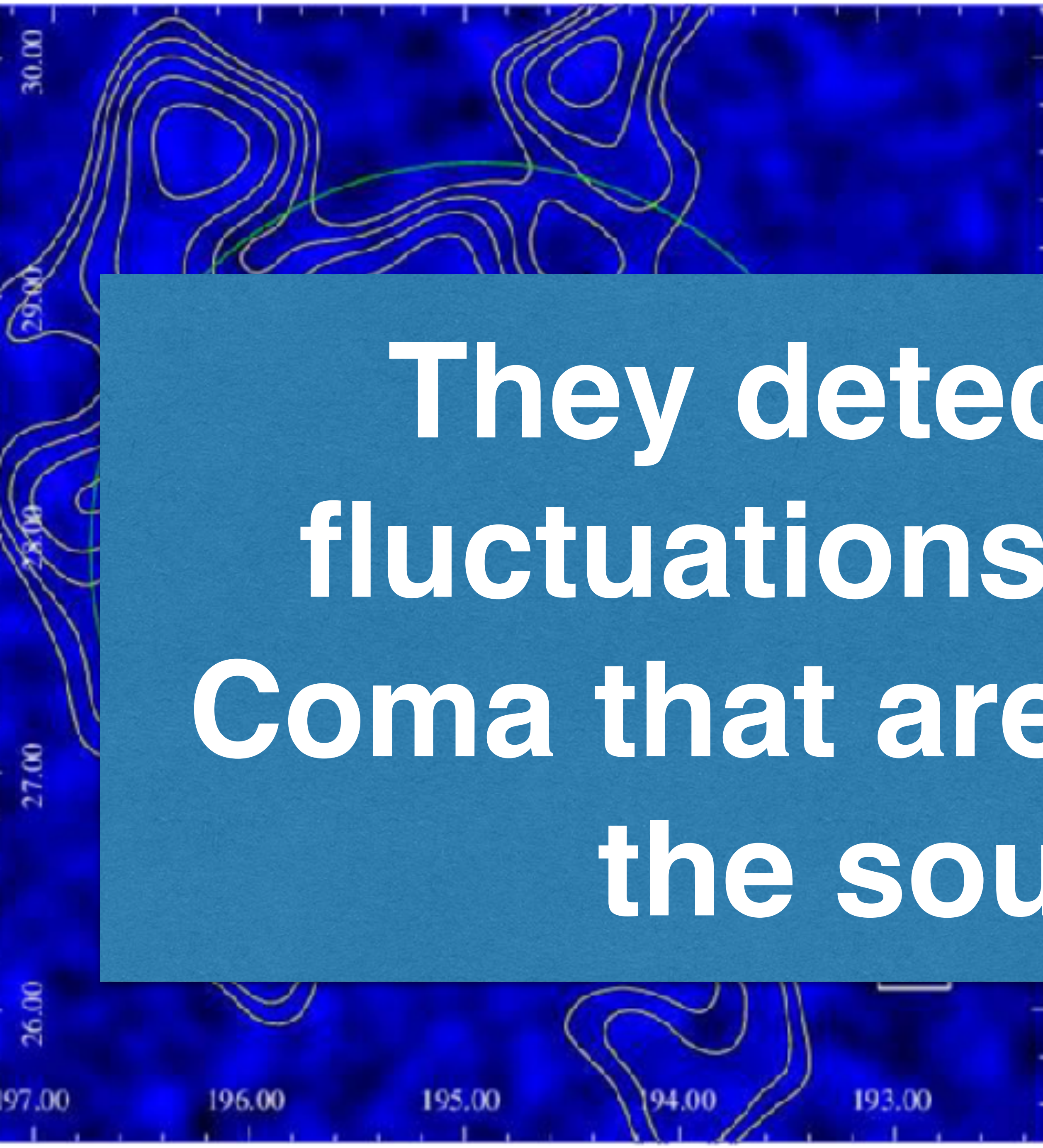
Coma

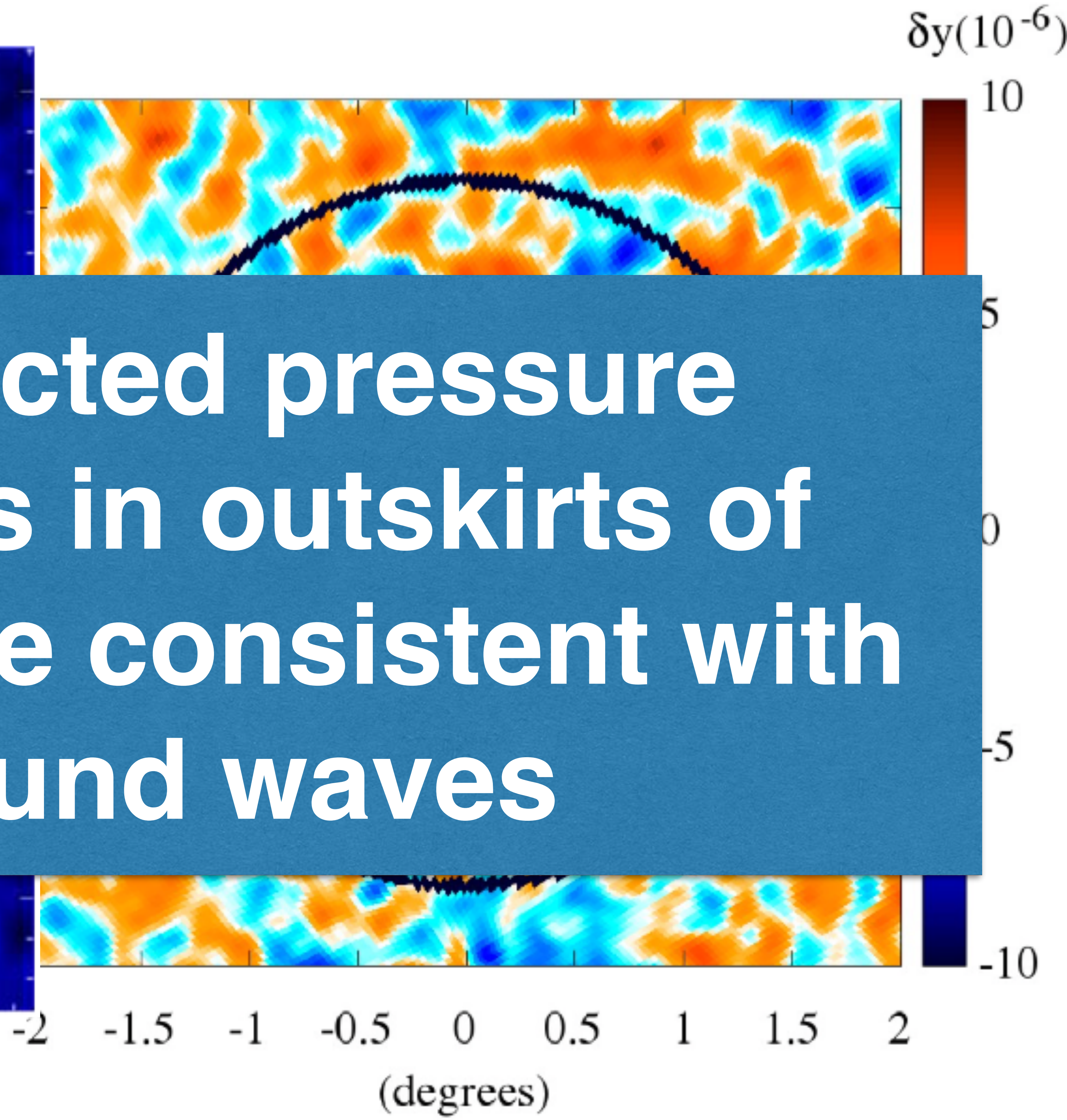




Planck Collaboration (2013) *R. Khatri & M. Gaspari (2016)*

Coma





They detected pressure fluctuations in outskirts of Coma that are consistent with the sound waves

Planck Collaboration (2013)

R. Khatri & M. Gaspari (2016)

A Picture

- In the outskirts of a galaxy cluster, mass still accretes, creating weak shocks (M~a few)
  - The effective equation of state of pressure fluctuations is <u>adiabatic</u>
- In the core of a cluster, gas is just pushed around by sloshing, buoyancy, etc, without changing pressure
  - The effective equation of state of pressure fluctuations is <u>isobaric</u>
- This kind of study has been done by “pressure” estimated from X-ray data (Churazov et al. 2012; 2016; many others), but we can finally do this with **real** pressure from high-resolution SZ data!

Secondary Anisotropies: Structure Formation seen in the CMB

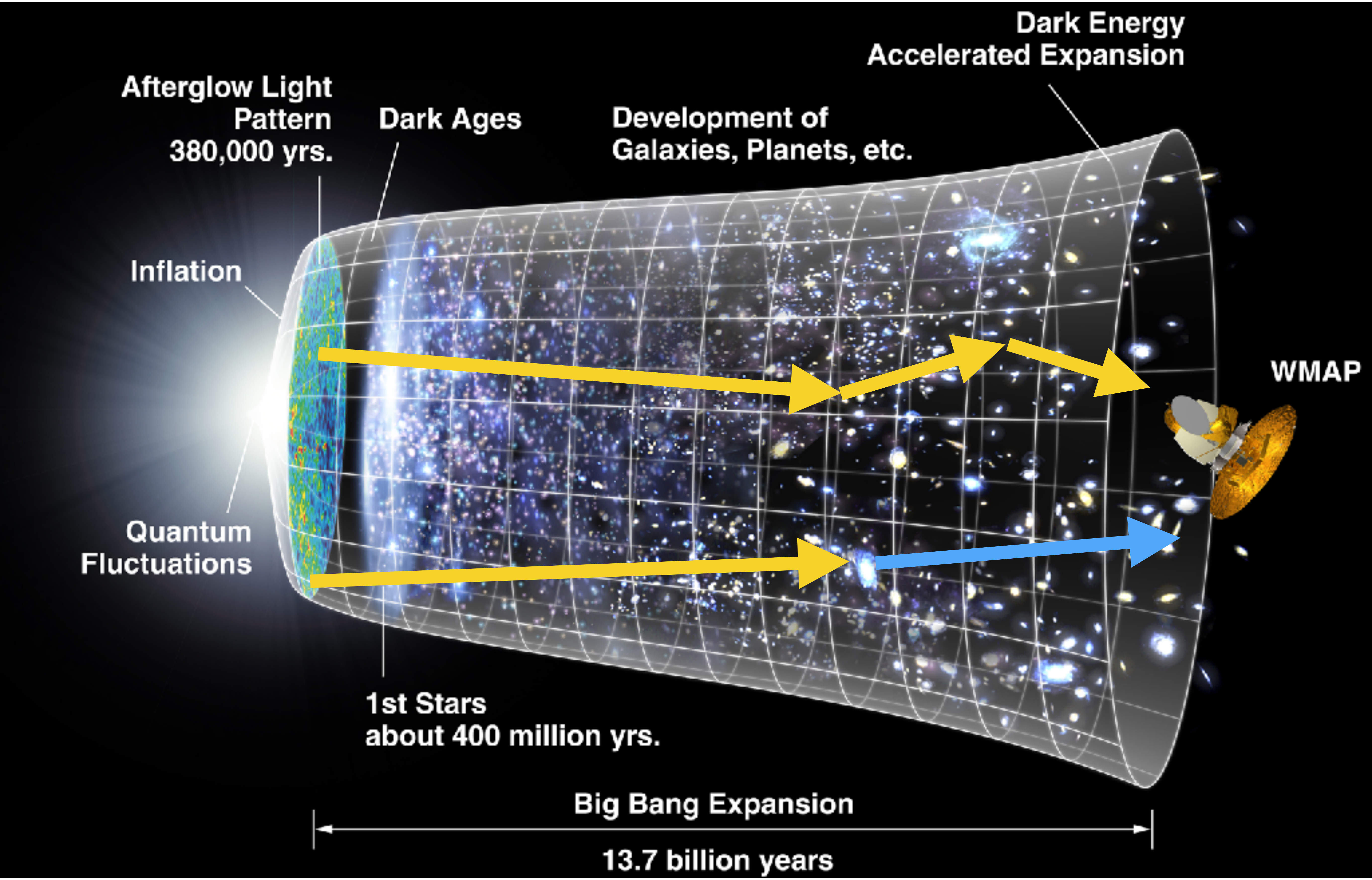
Gravitational Lensing

- Matter bends light of the CMB

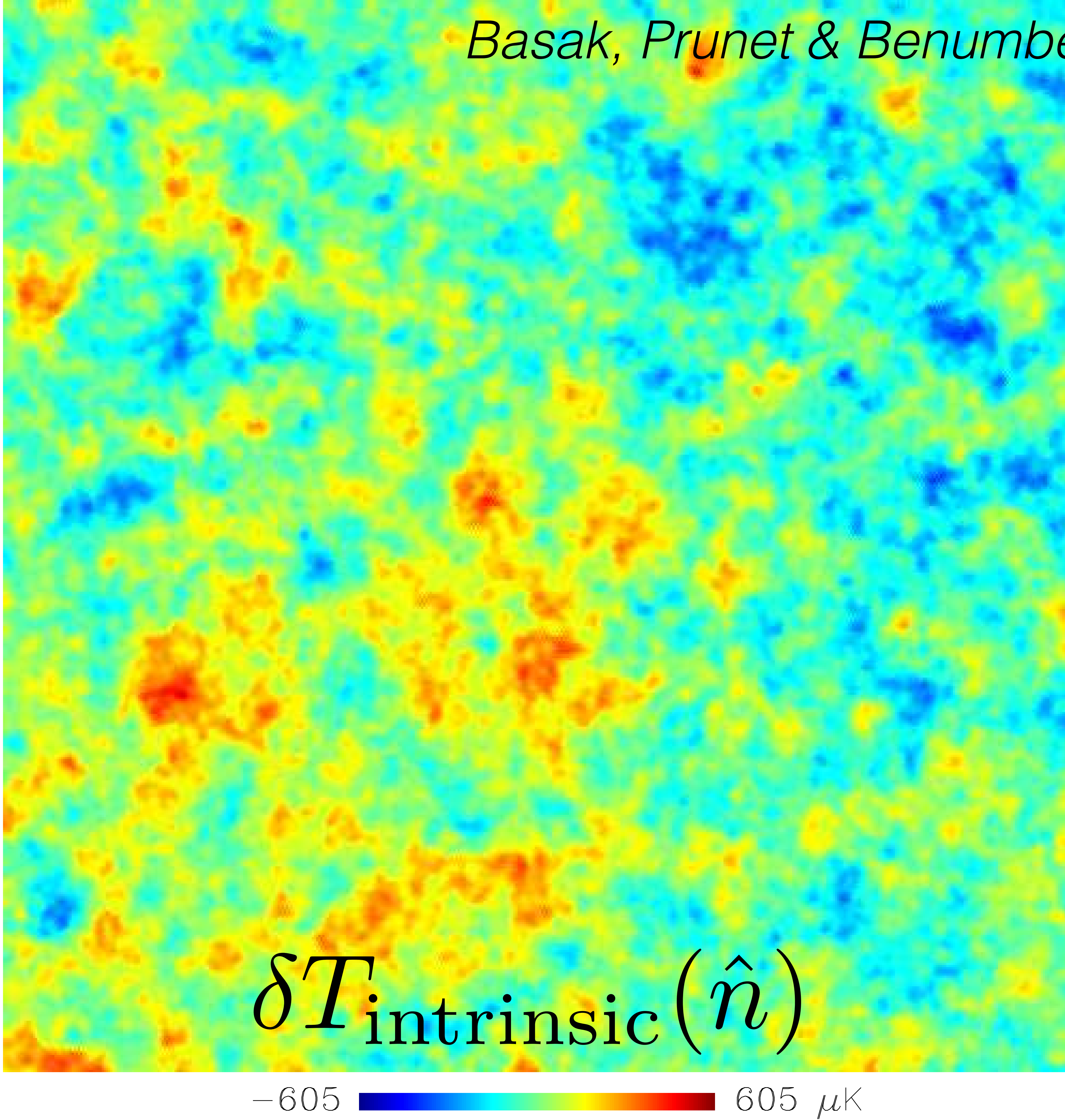
Sunyaev-Zel'dovich Effect

- Electrons in hot, collapsed gas up-scatter low-energy CMB photons, distorting the black-body spectrum of the CMB

- Both have been measured, providing the key insights into how the structures grew out of initial conditions. **Initial conditions to structure formation**, using the CMB data only!

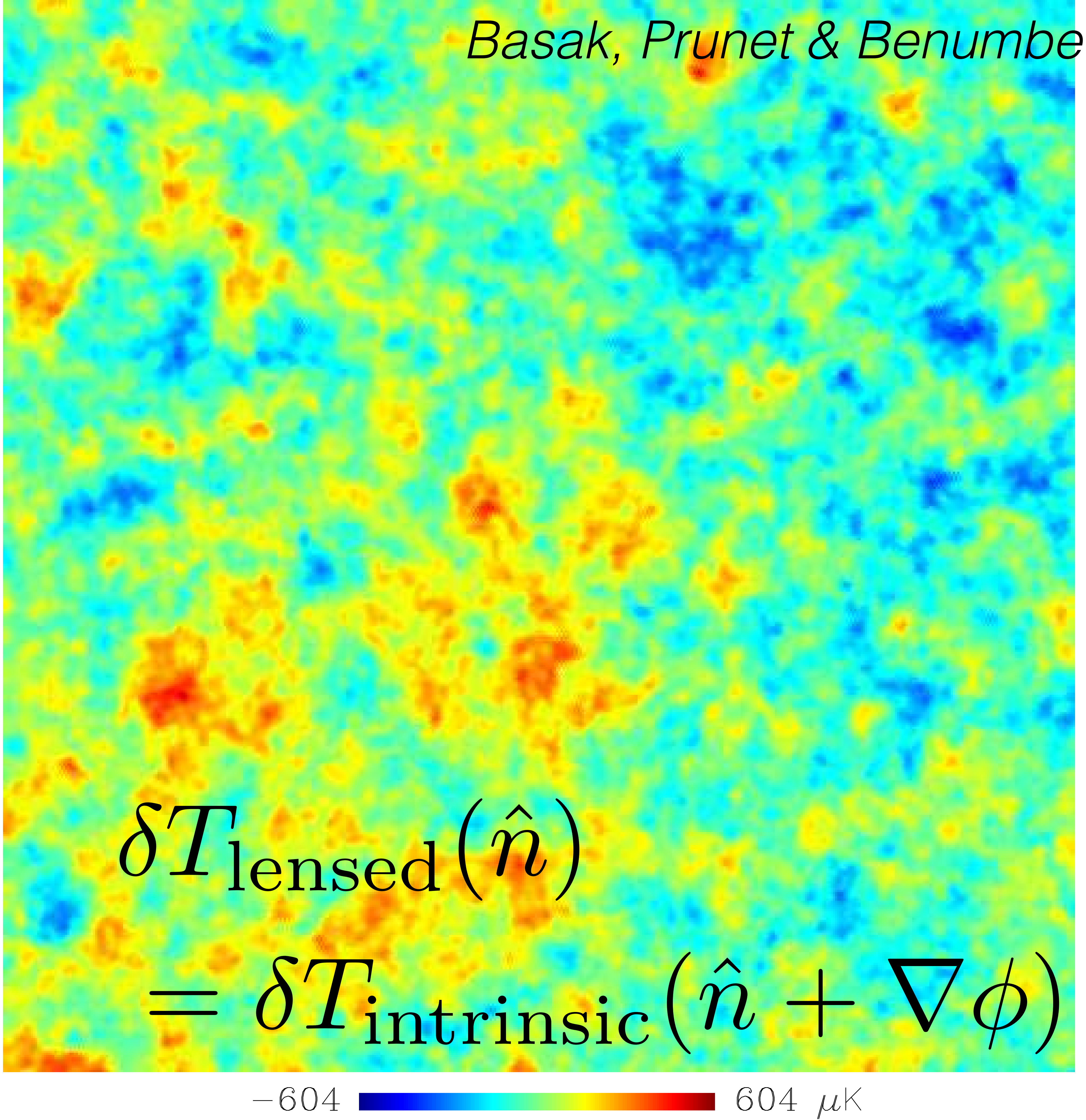

Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Basak, Prunet & Benumbed (2008)

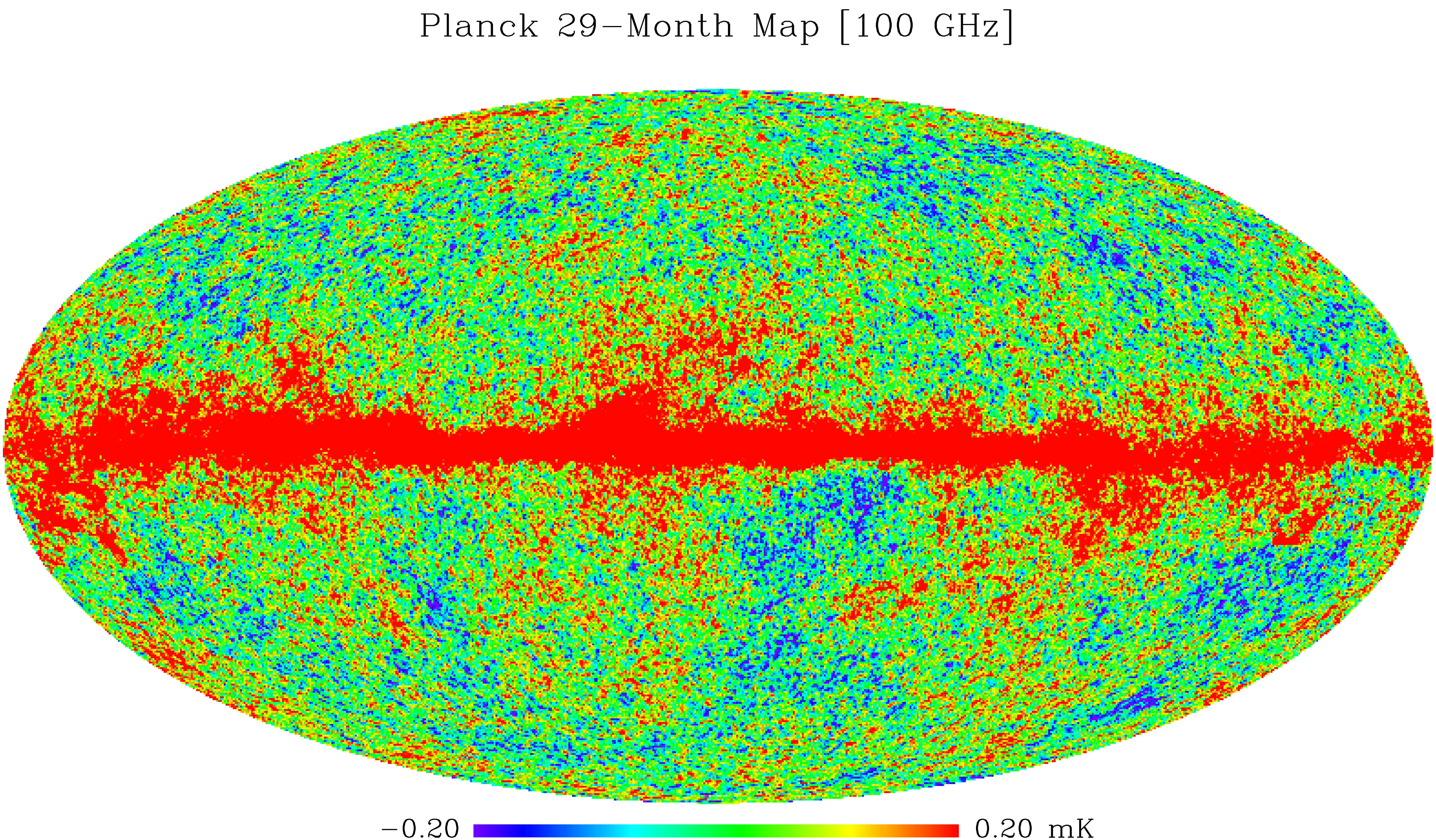


$$\delta T_{\rm intrinsic}(\hat{n})$$

Basak, Prunet & Benumbed (2008)

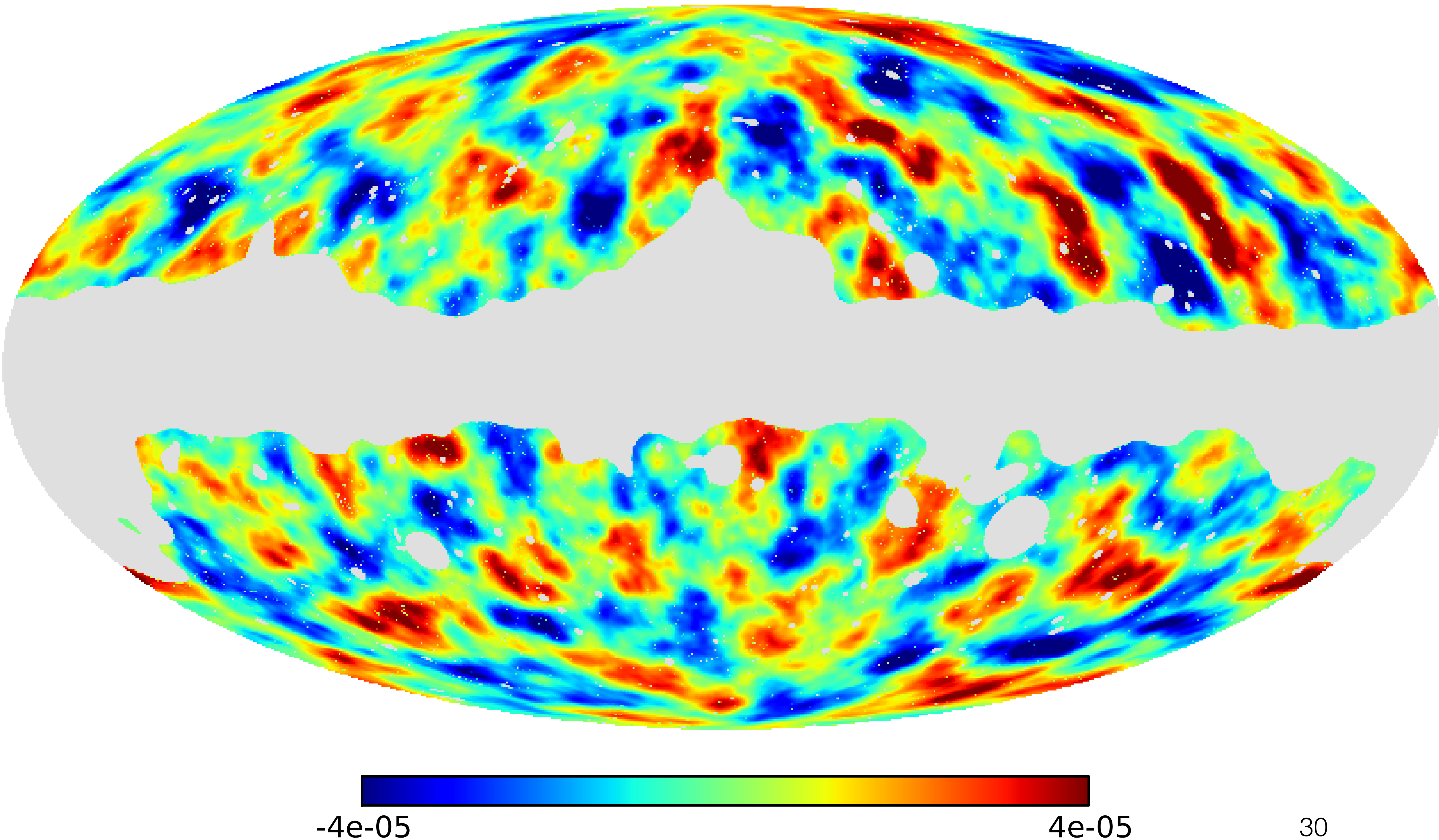


$$\delta T_{\text{lensed}}(\hat{n}) = \delta T_{\text{intrinsic}}(\hat{n} + \nabla \phi)$$

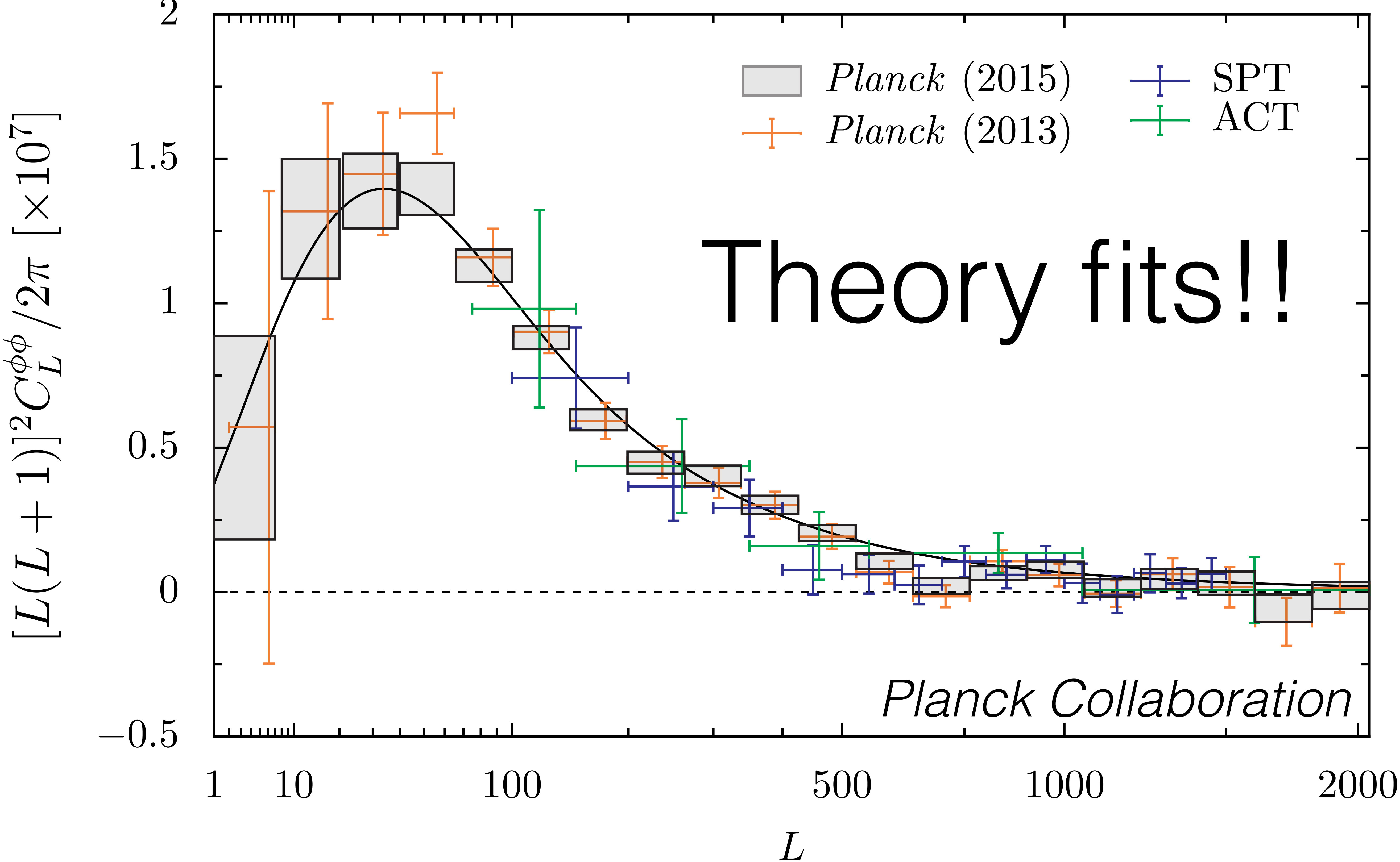


From full-sky temperature maps to…

Planck Collaboration



A full-sky lensing potential map!

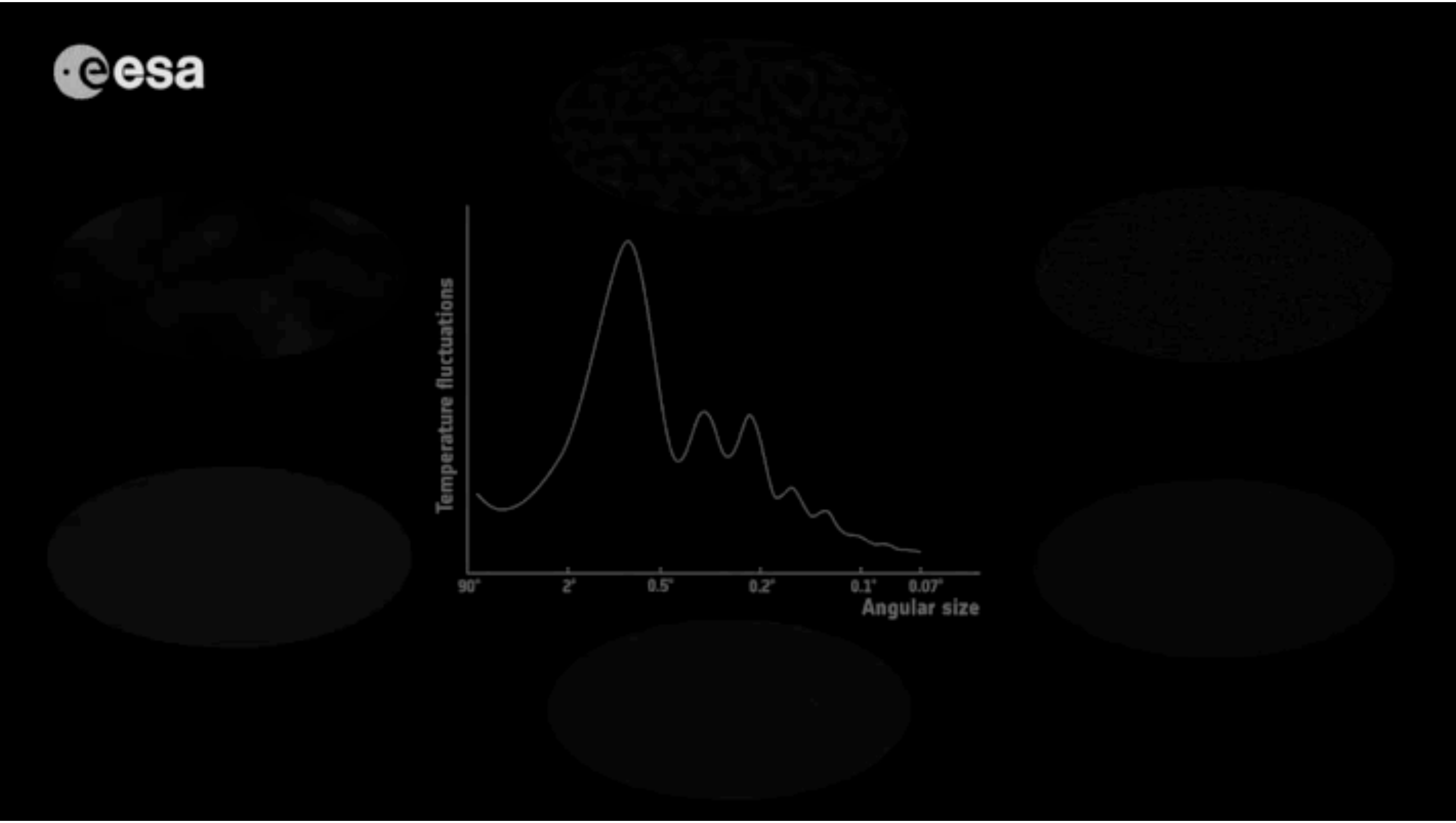


...and our knowledge of the matter distribution improves

$$\Omega_m = 0.315 \pm 0.013$$
$$\sigma_8 = 0.829 \pm 0.014$$

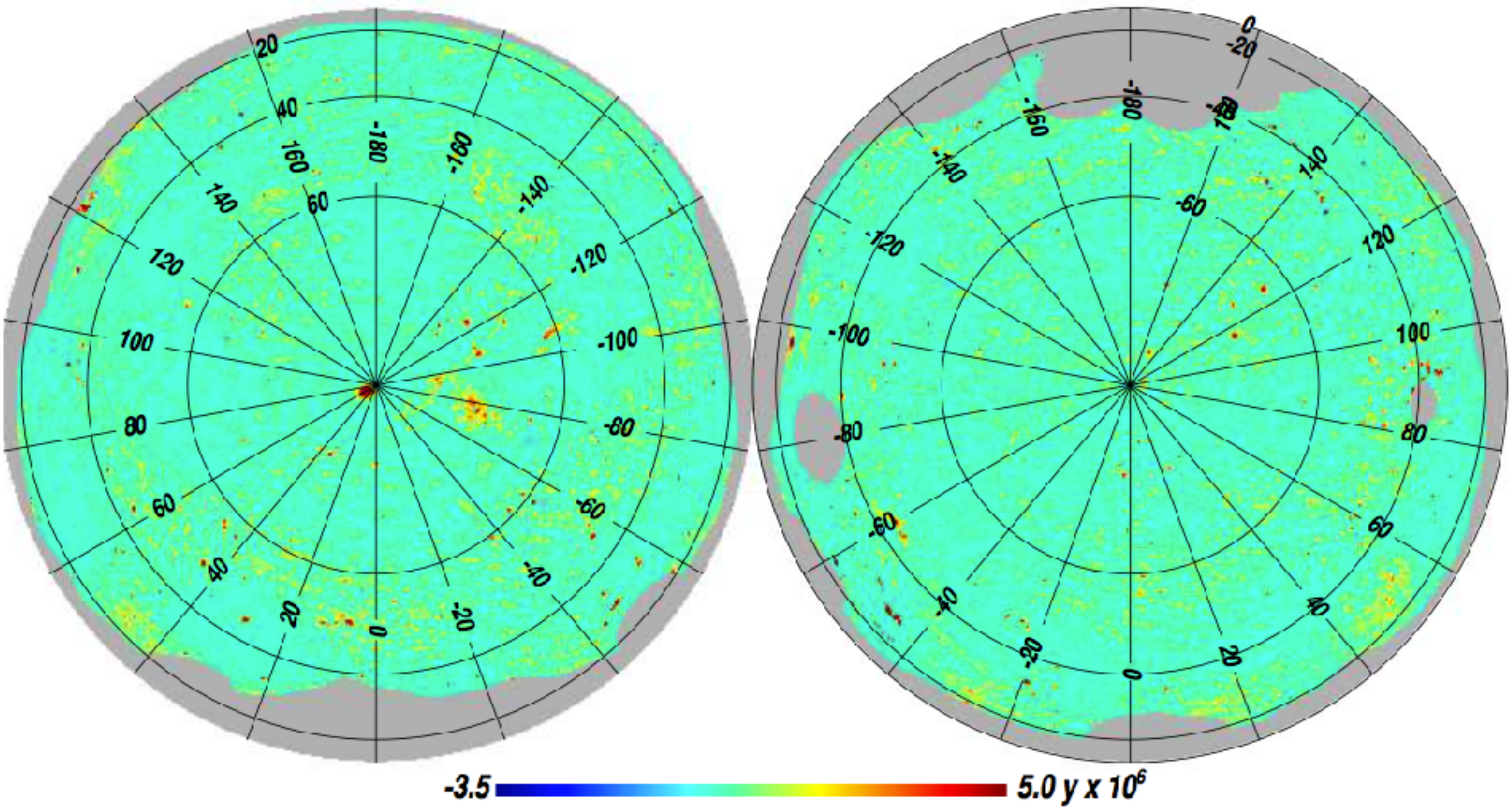
Adding the lensing info

$$\Omega_m = 0.308 \pm 0.012$$
$$\sigma_8 = 0.8149 \pm 0.0093$$


Temperature fluctuations
90°
2°
0.5°
0.2°
0.1°
0.07°
Angular size

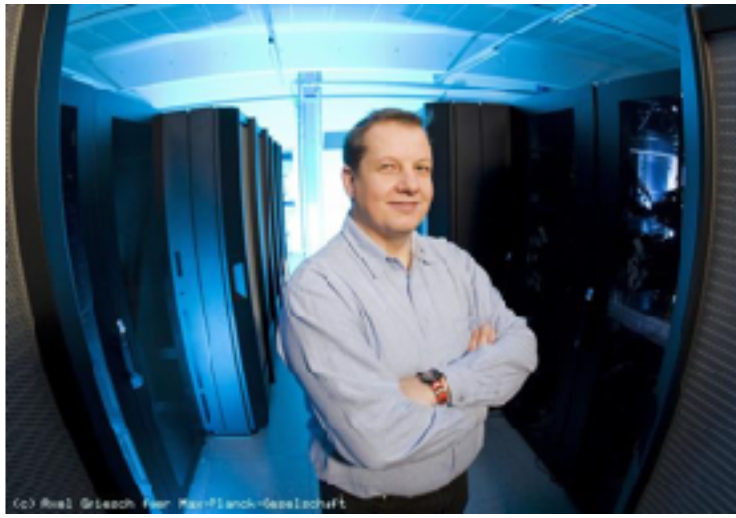
Full-sky Thermal Pressure Map

North Galactic Pole — MILCA tSZ map — South Galactic Pole



Planck Collaboration

We can simulate this


Klaus Dolag (MPA/LMU)

arXiv:1509.05134 [accepted for publication in MNRAS]

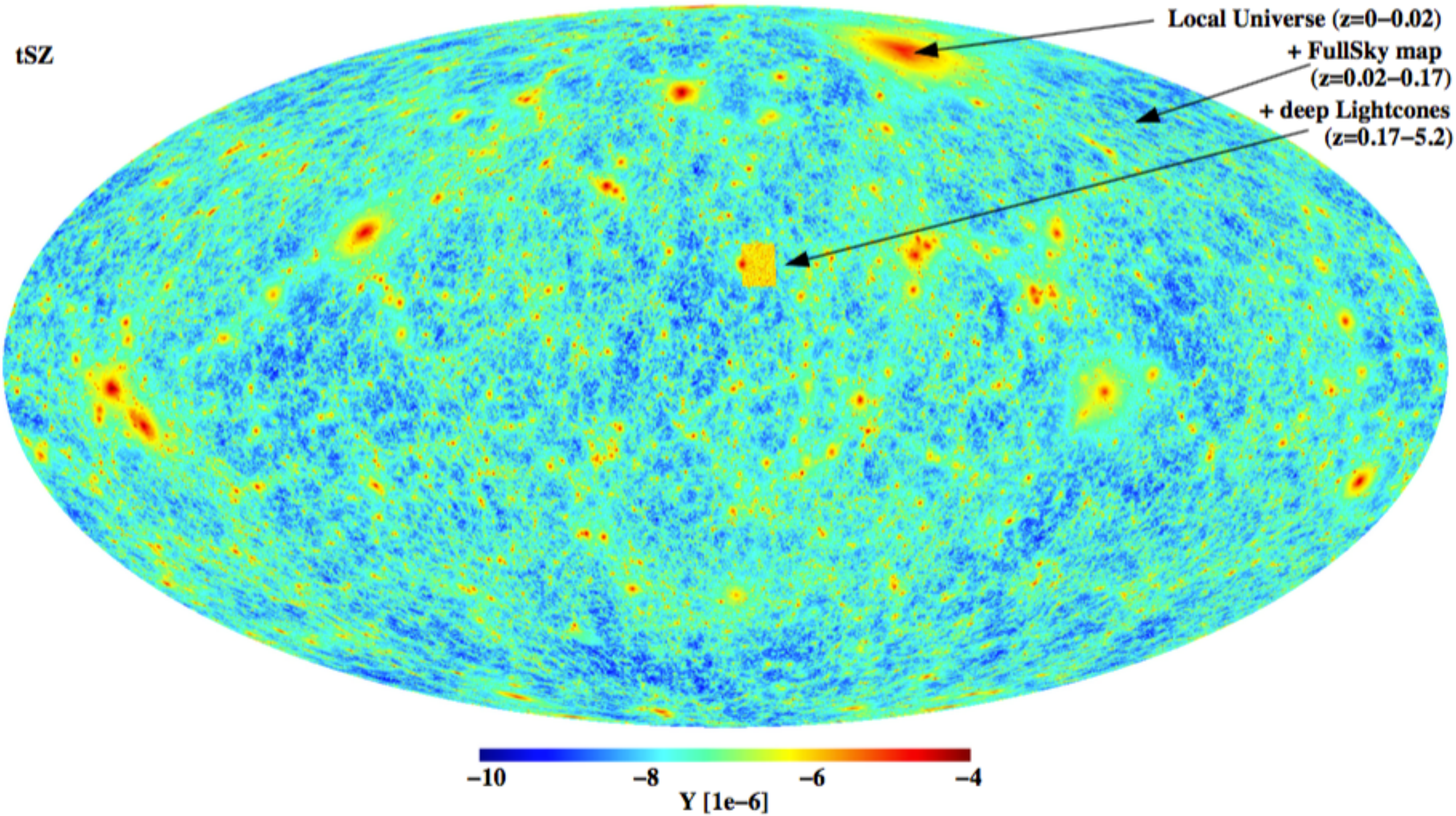
SZ effects in the Magneticum Pathfinder Simulation: Comparison with the Planck, SPT, and ACT results

K. Dolag[1,2*], E. Komatsu[2,3] and R. Sunyaev[2,4]

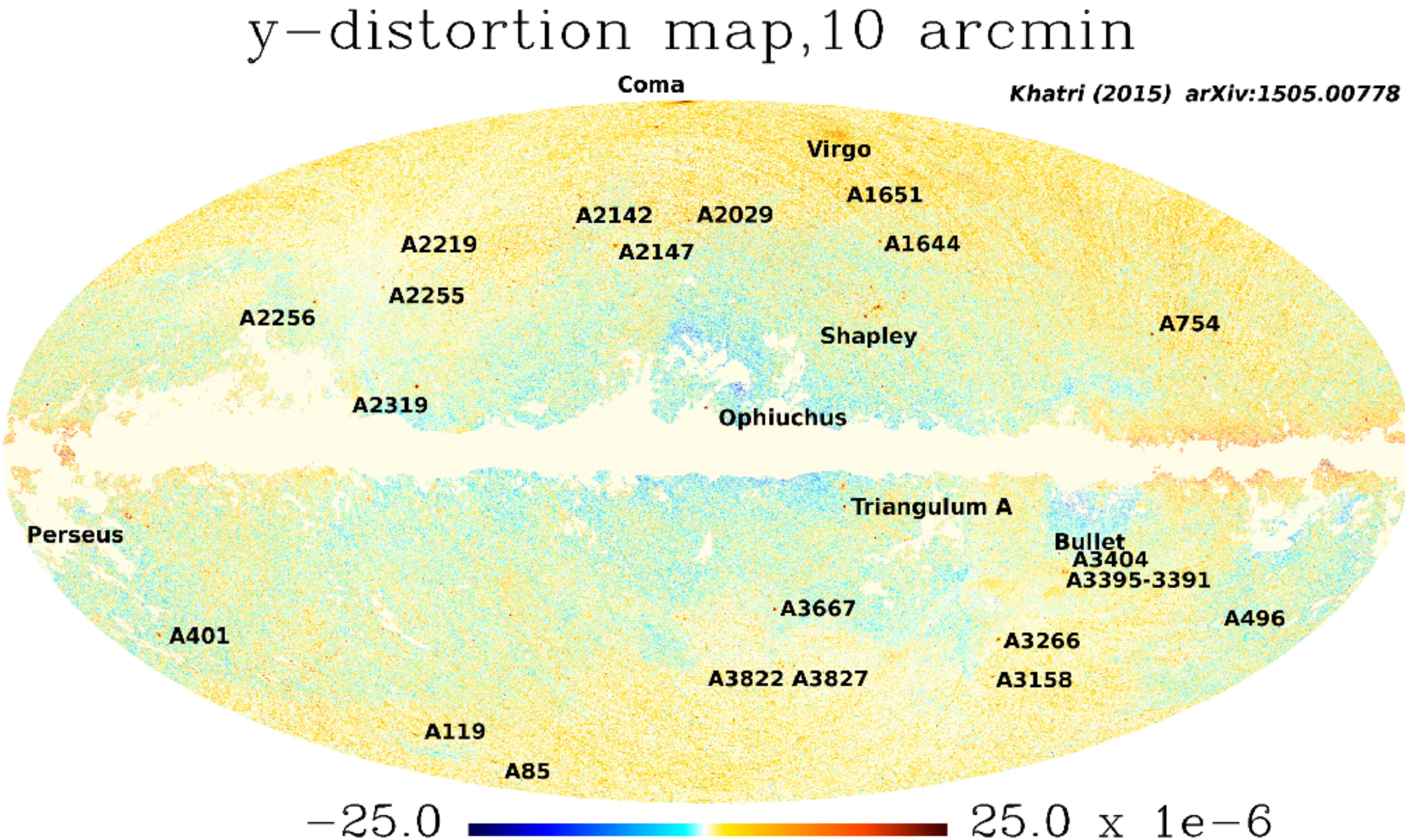
[1] *University Observatory Munich, Scheinerstr. 1, 81679 Munich, Germany*
[2] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild Strasse 1, 85748 Garching, Germany*
[3] *Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa 277-8583, Japan*
[4] *Space Research Institute (IKI), Russian Academy of Sciences, Profsoyuznaya str. 84/32, Moscow, 117997 Russia*

- Volume: $(896 \text{ Mpc/h})^3$
- Cosmological hydro (P-GADGET3) with star formation and AGN feed back
- 2×1526^3 particles ($m_{DM}=7.5 \times 10^8$ M_{sun}/h)

Dolag, EK, Sunyaev (2016)

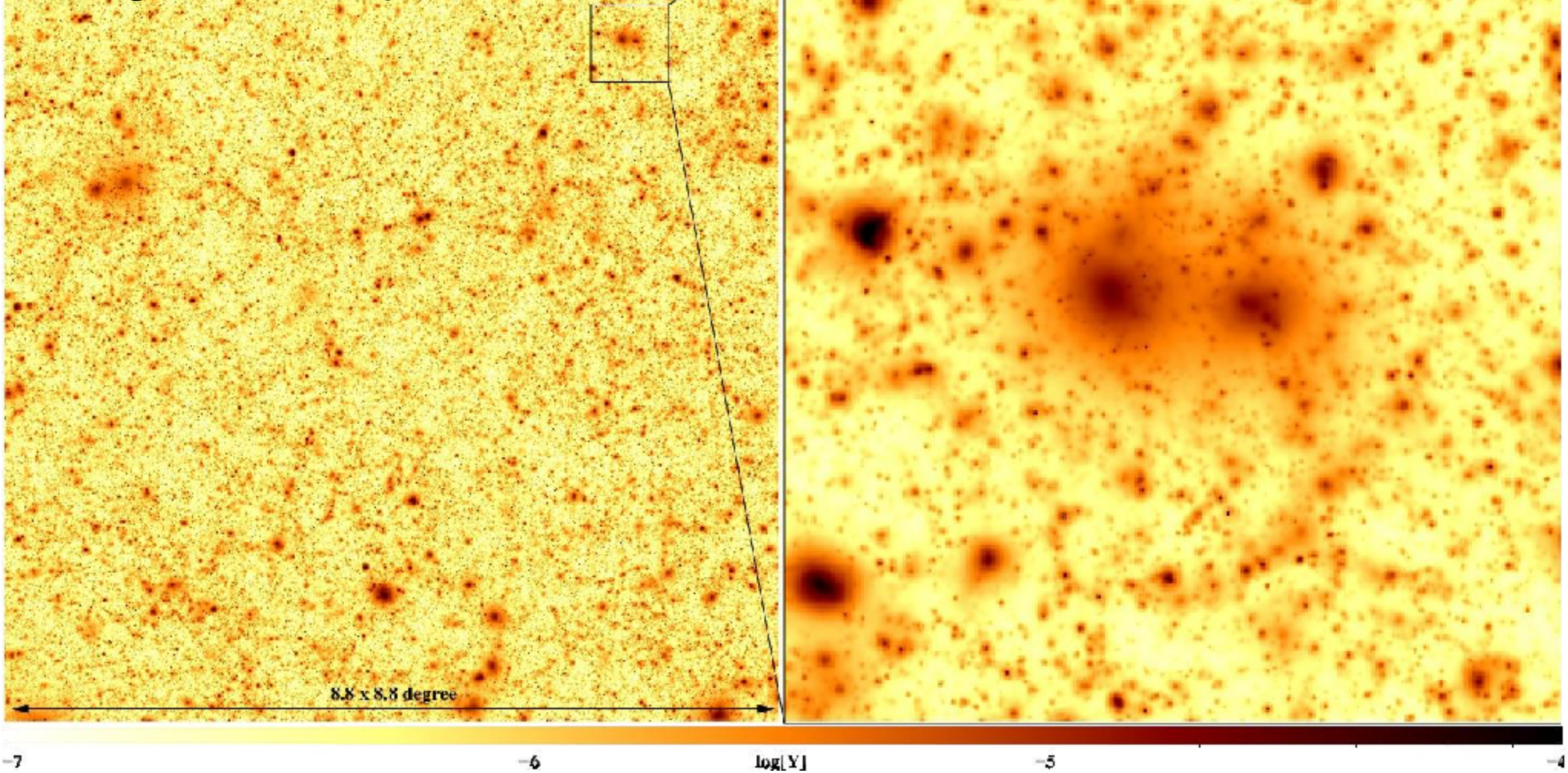


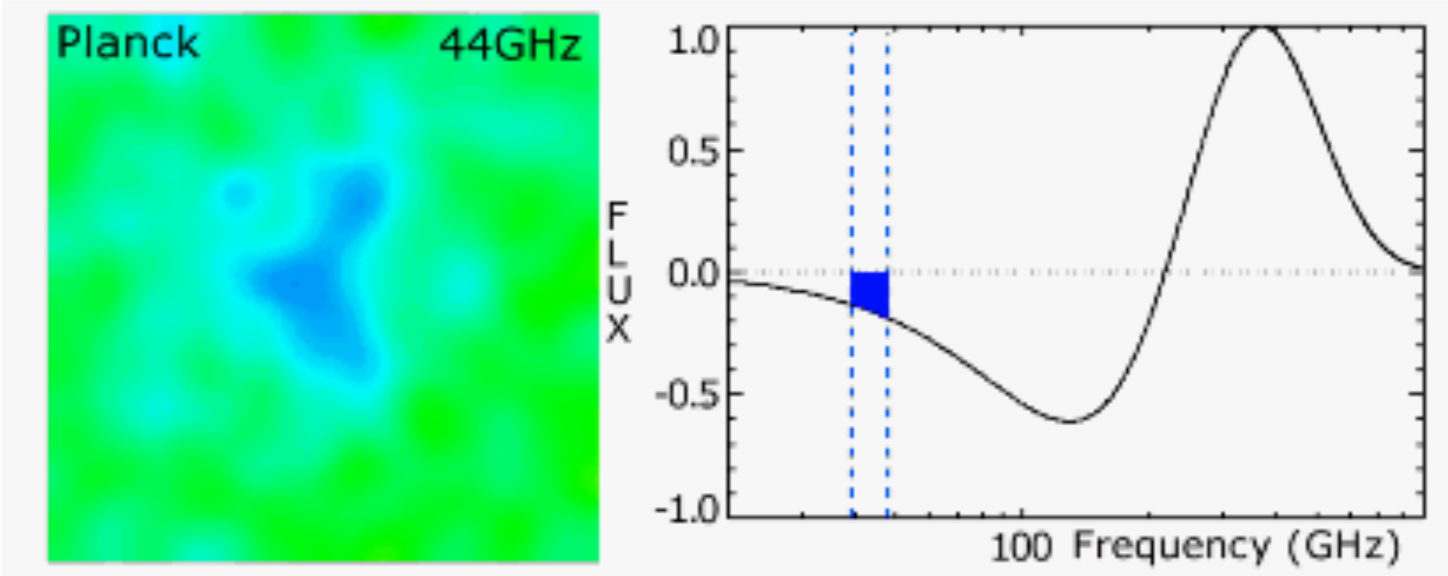
$$Y_{\rm tSZ}(\boldsymbol{\theta}) = \frac{k_B \sigma_T}{m_e c^2} \int {\rm d}l\, n_e(\boldsymbol{\theta}, l)\, T(\boldsymbol{\theta}, l)$$



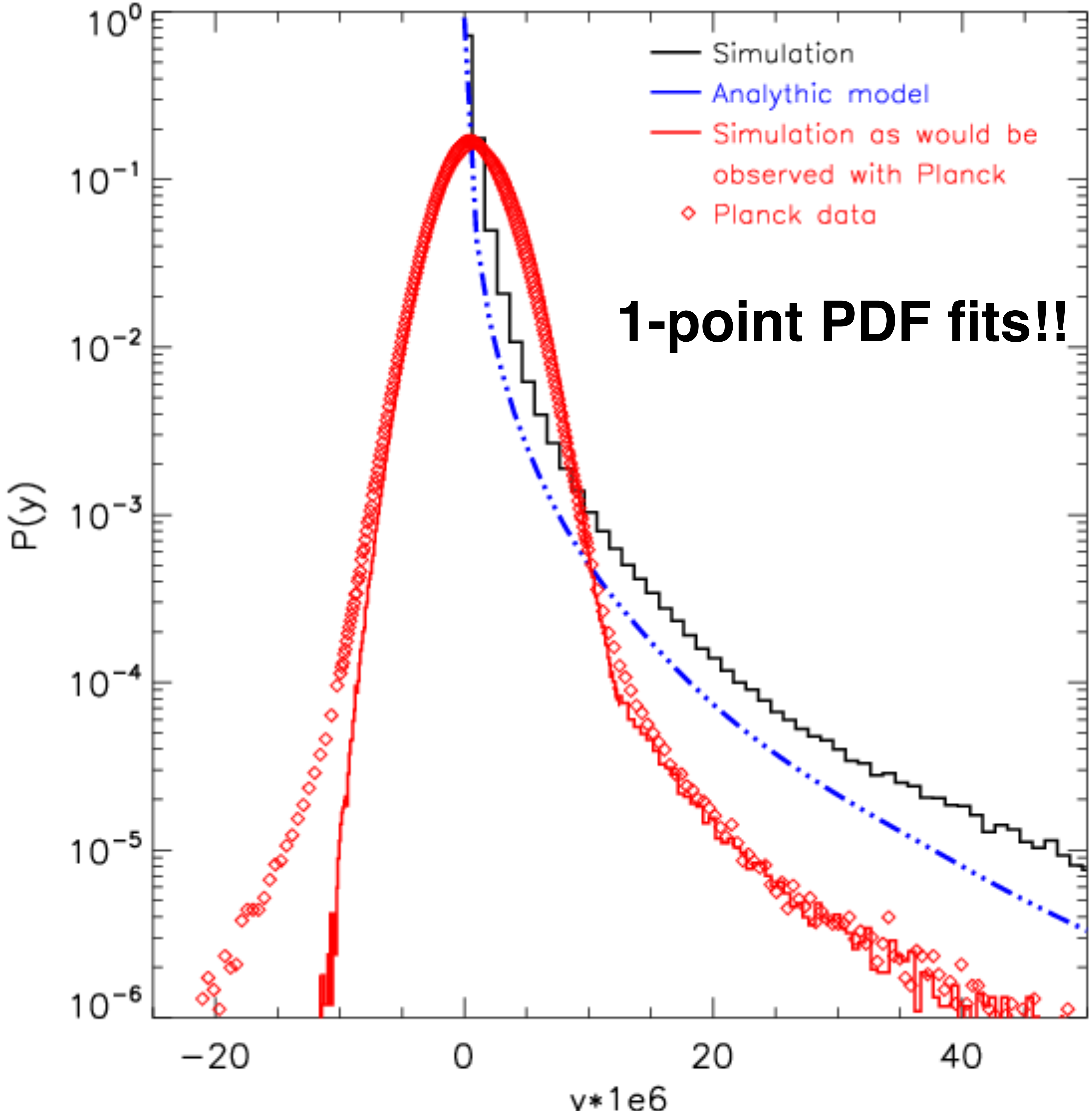
- “The local universe simulation” reproduces the observed structures pretty well

Dolag, EK, Sunyaev (2016)

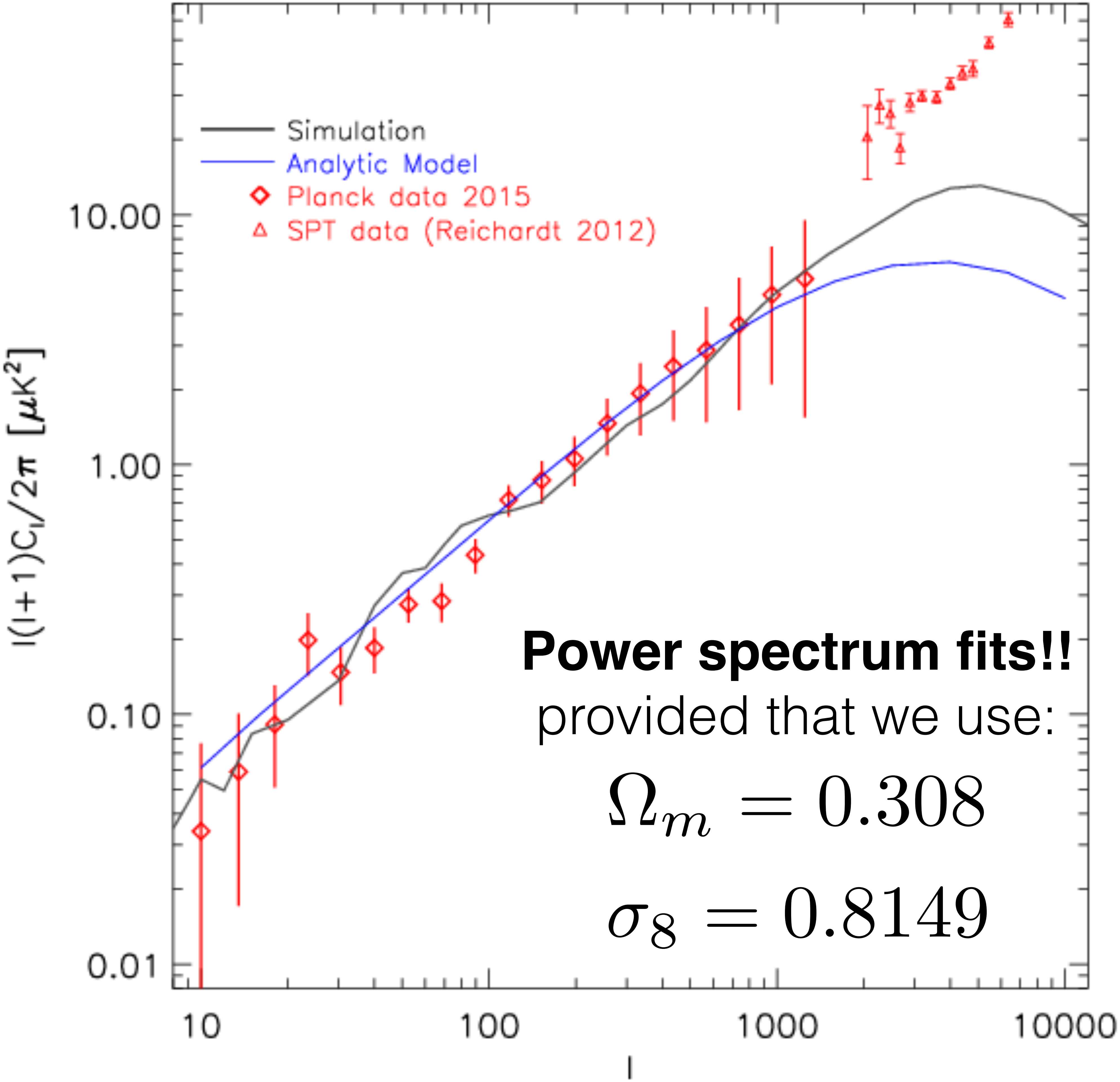




Dolag, EK, Sunyaev (2016)



Dolag, EK, Sunyaev (2016)



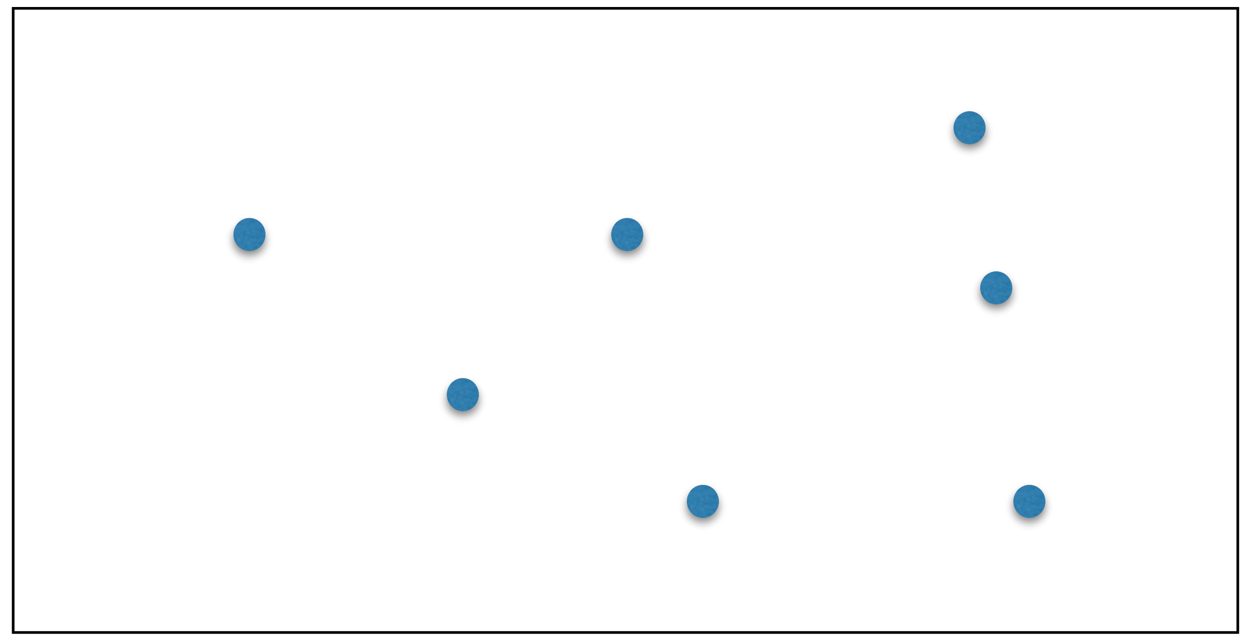
Power spectrum fits!!

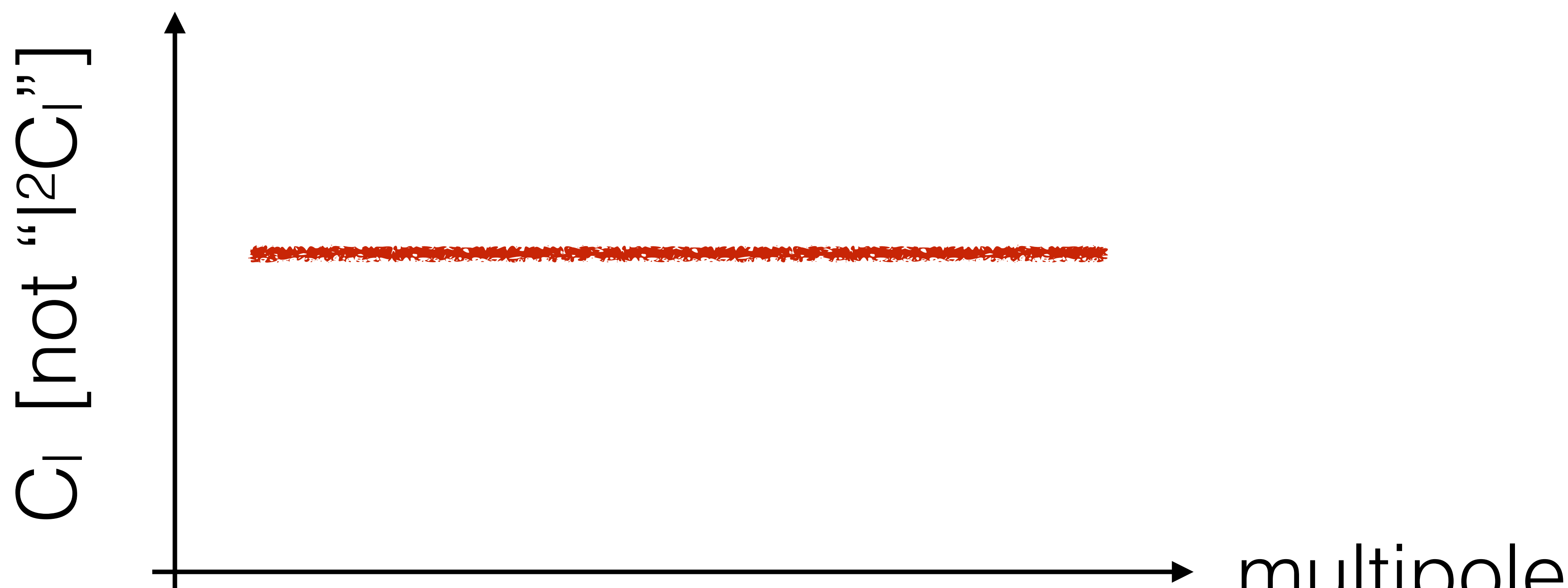
provided that we use:

$$\Omega_m = 0.308$$

$$\sigma_8 = 0.8149$$

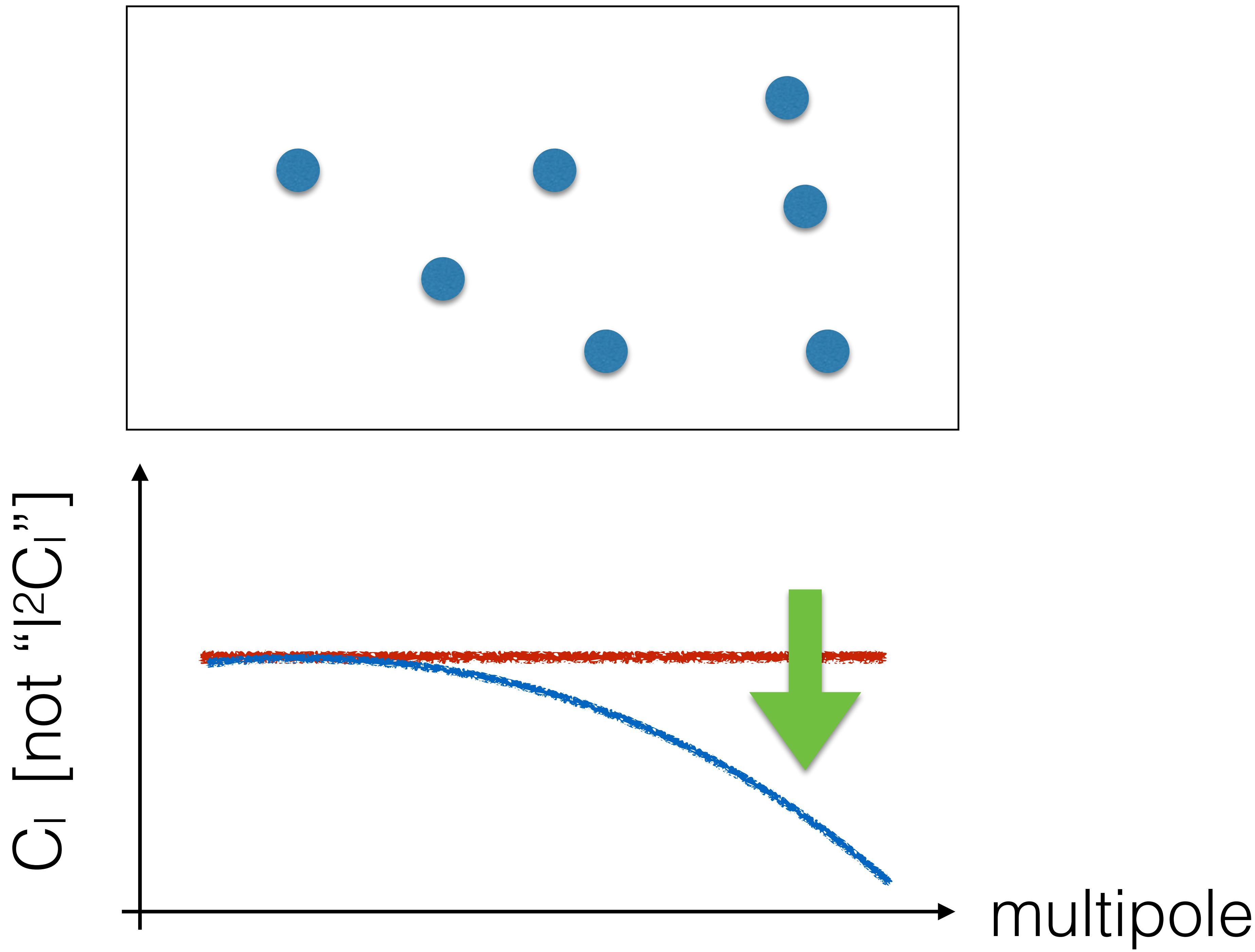
Simple Interpretation



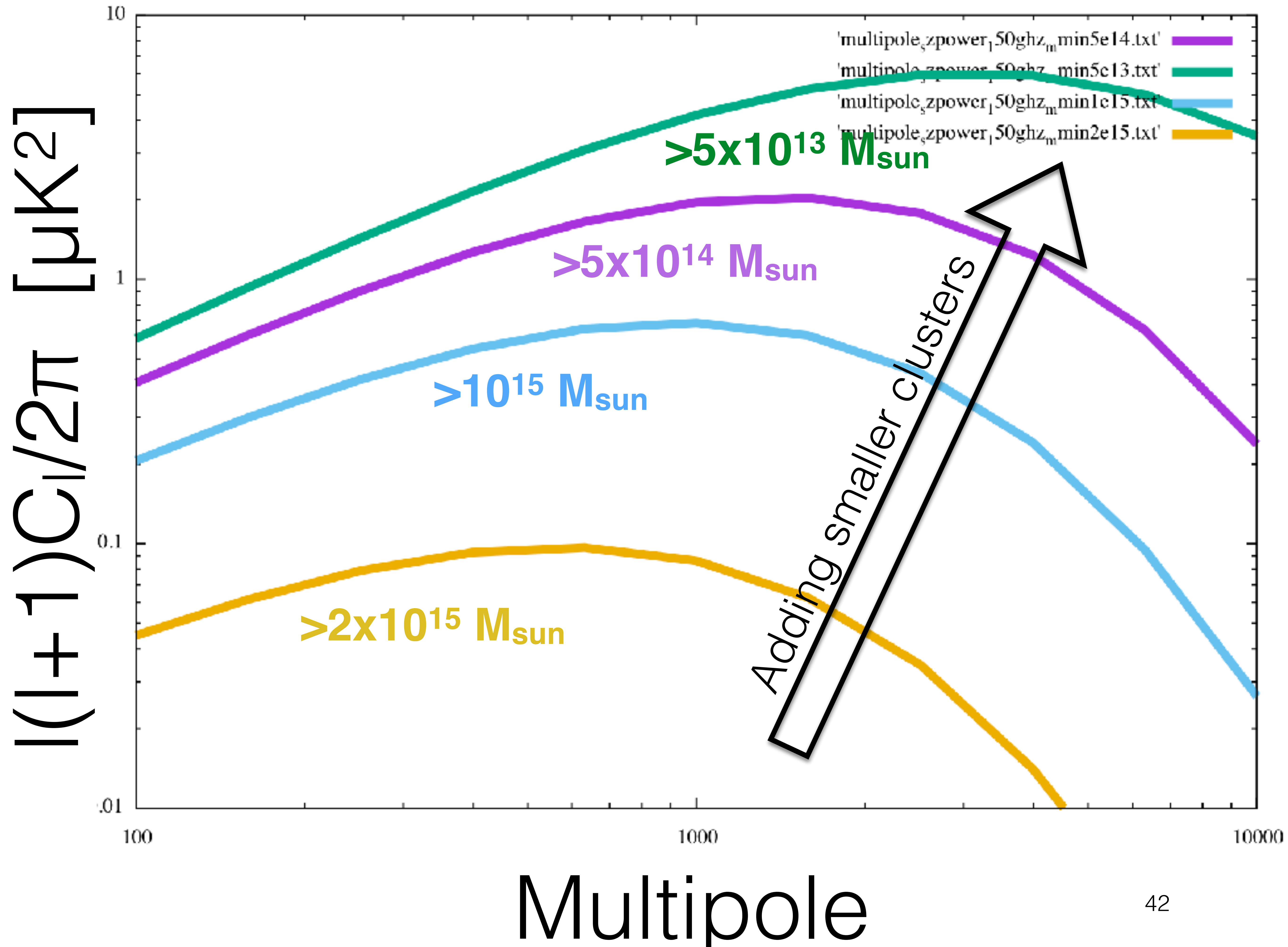


- Randomly-distributed point sources = Poisson spectrum = $\sum_i(\text{flux}_i)^2 / 4\pi$

Simple Interpretation



- Extended sources = the power spectrum reflects intensity profiles



'multipole_szpower_150ghz_mmin5e14.txt'
'multipole_szpower_150ghz_mmin5e13.txt'
'multipole_szpower_150ghz_mmin1e15.txt'
'multipole_szpower_150ghz_mmin2e15.txt'
>5x10^13 M_sun
>5x10^14 M_sun
>10^15 M_sun
>2x10^15 M_sun
Adding smaller clusters
10
1
0.1
.01
100
1000
10000
l(l+1)C_l/2π [μK^2]
Multipole

Simple Formula

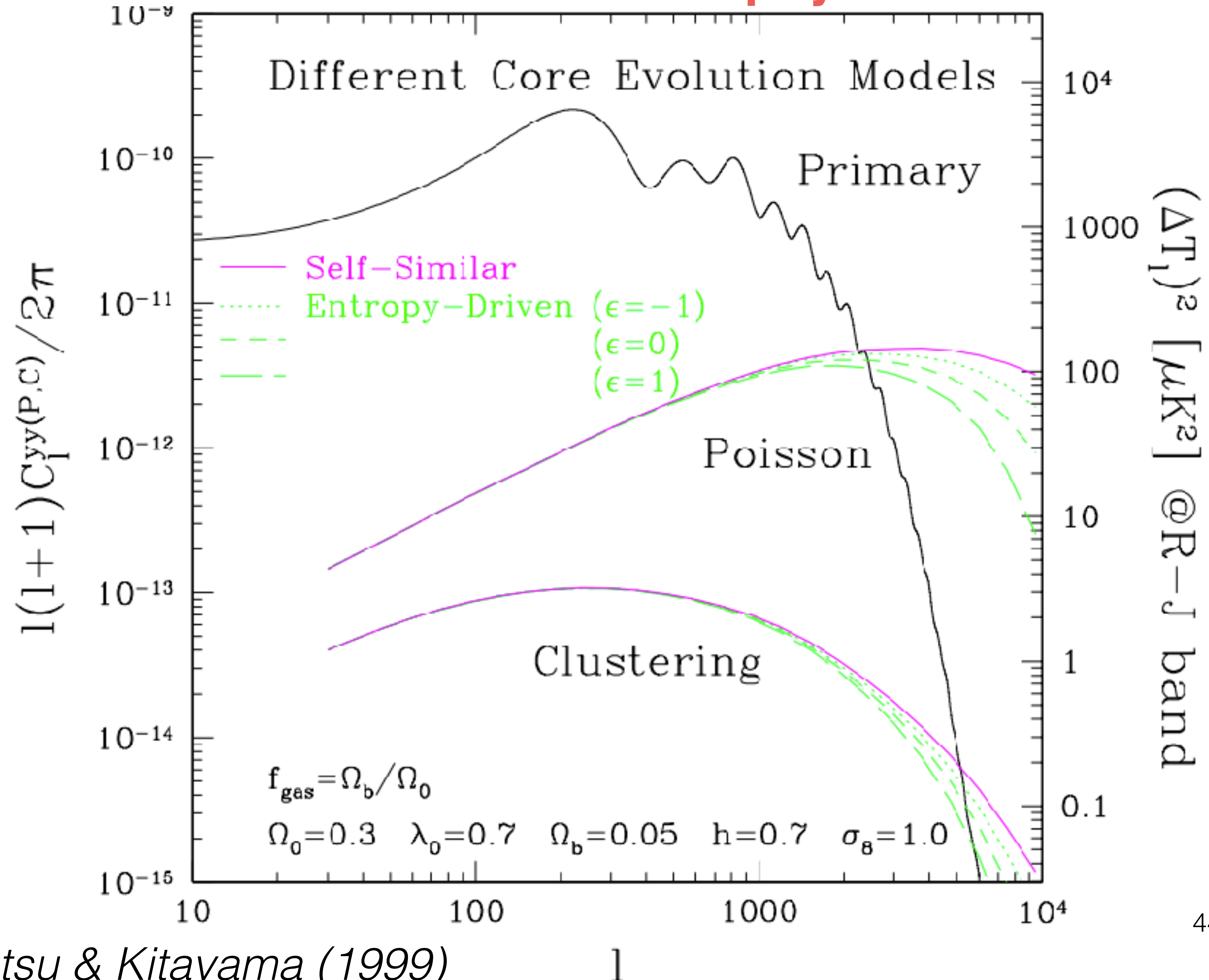
$$C_\ell = \int dz \frac{dV}{dz} \int dM \frac{dn}{dM} |y_\ell(M, z)|^2$$

2d Fourier transform of pressure

- y_l with small l just gives the total thermal pressure, MT ~ $M^{5/3}$
  - Heavily weighted by massive clusters
- The mass function, dn/dM, is sensitive to the amplitude of fluctuations, σ_8

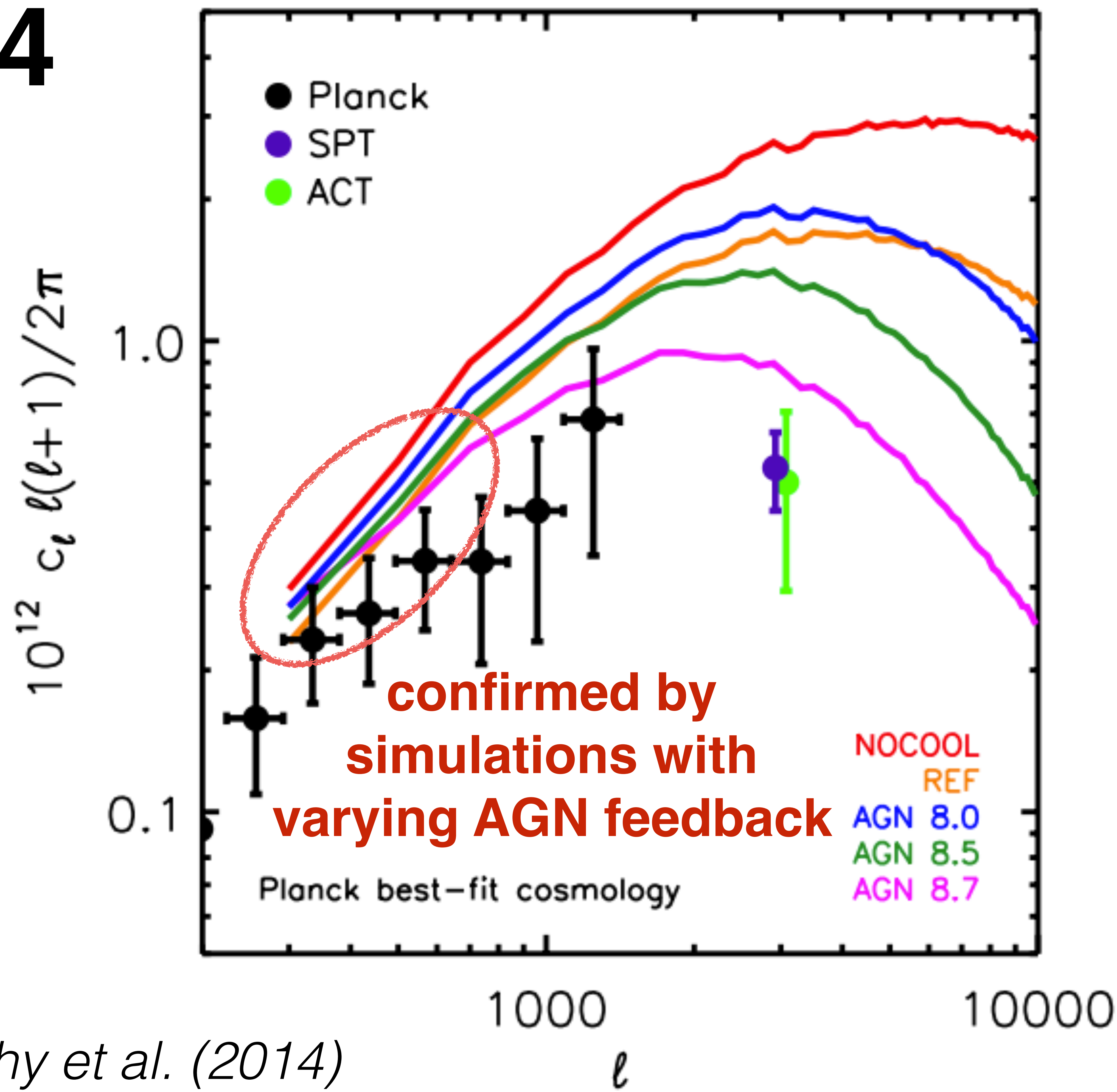
1999

Degree-scale SZ power spectrum is less sensitive to astrophysics in cluster cores



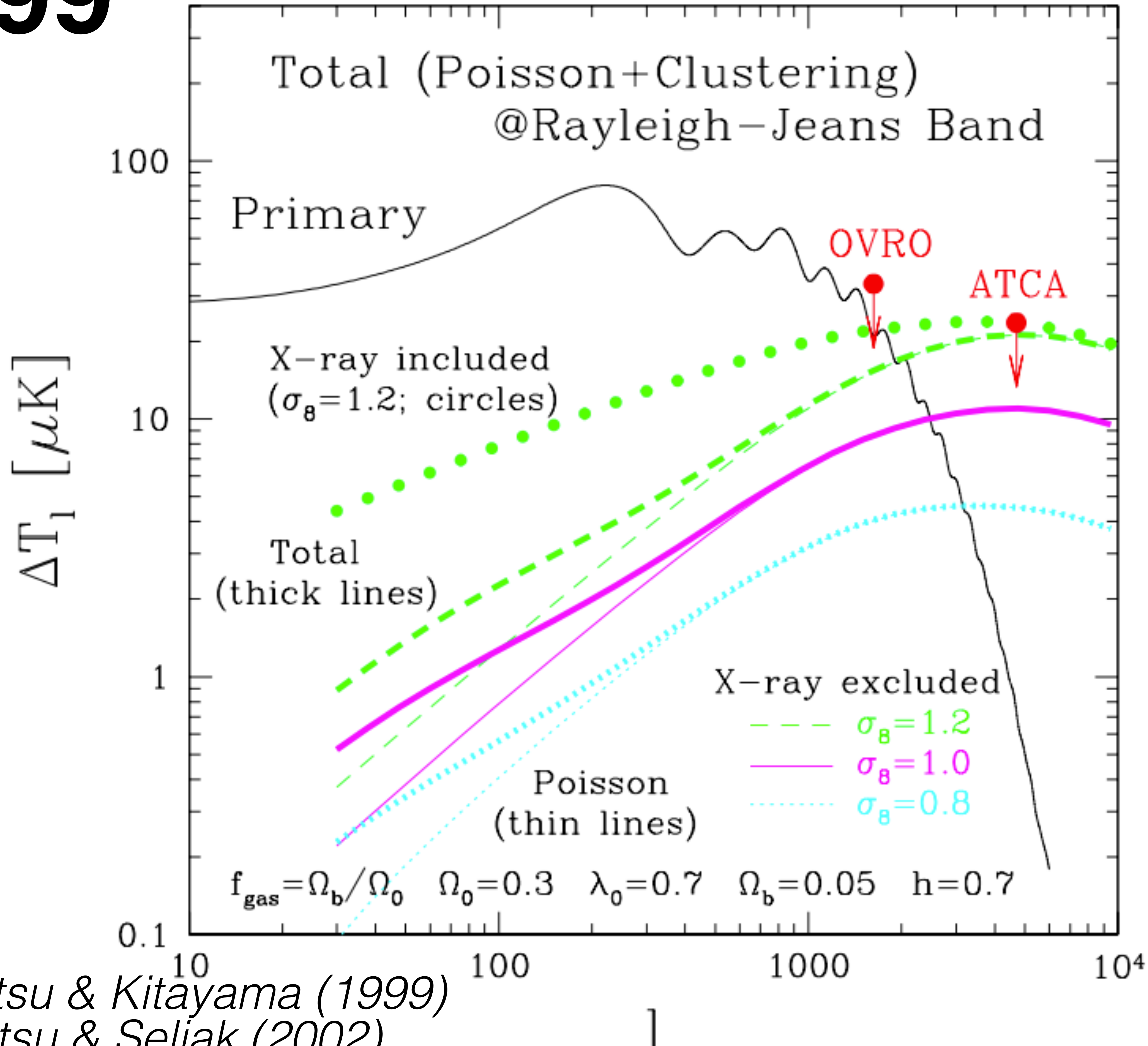
Komatsu & Kitayama (1999)

2014



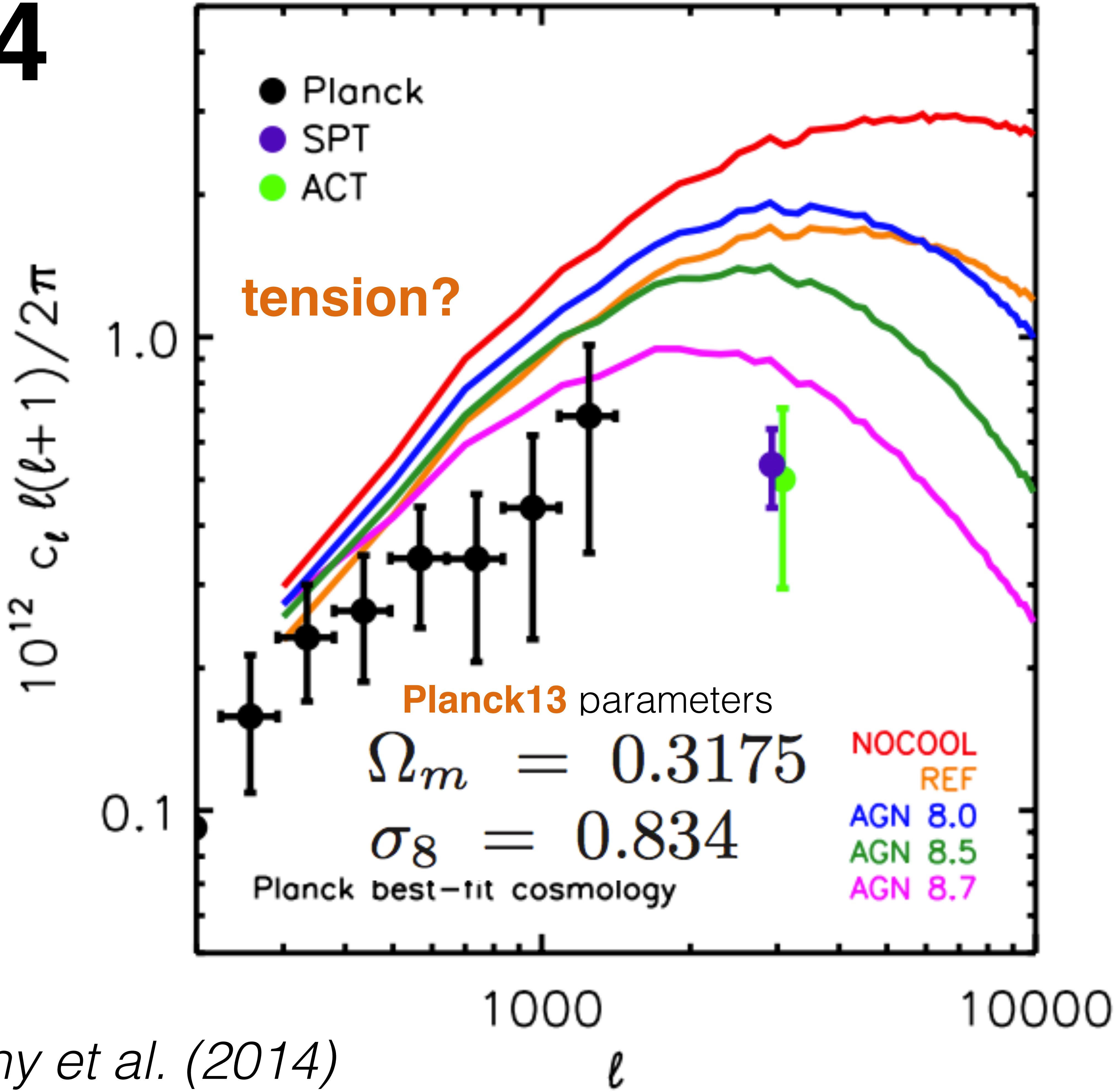
McCarthy et al. (2014)

1999 It is very sensitive to the amplitude of fluctuations



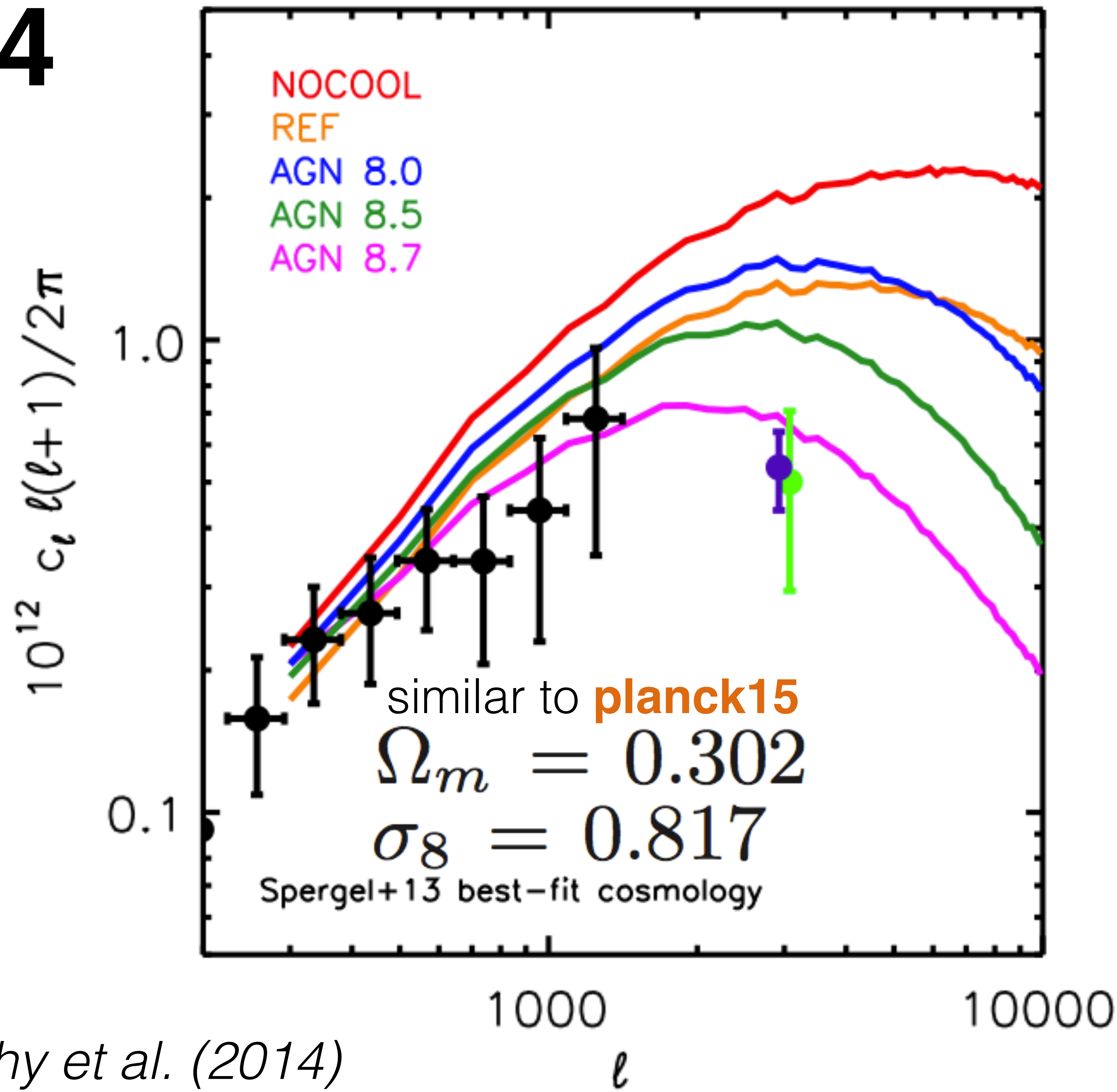
Komatsu & Kitayama (1999)
Komatsu & Seljak (2002)

2014



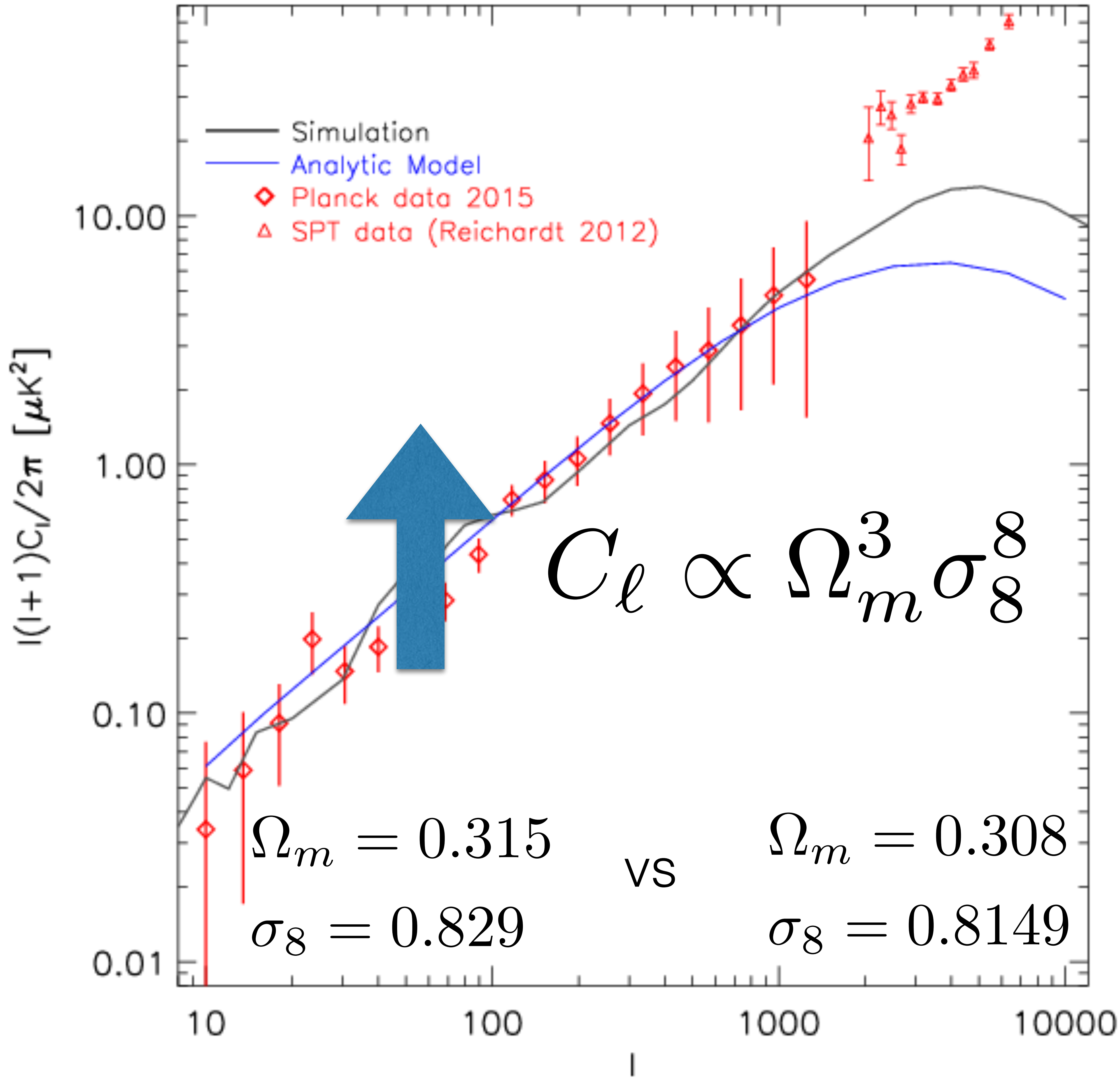
McCarthy et al. (2014)

2014



McCarthy et al. (2014)

Dolag, EK, Sunyaev (2016)

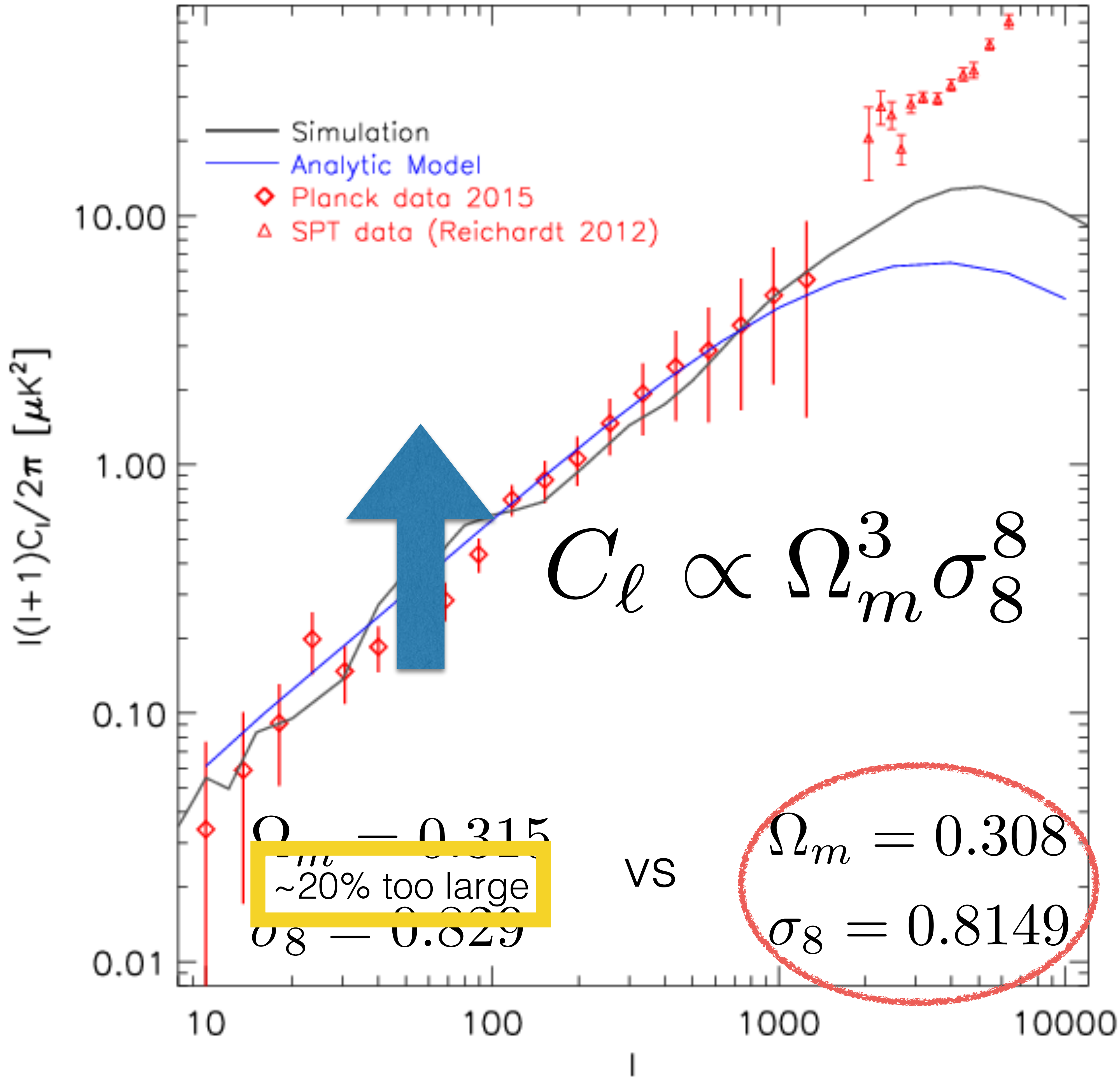


$$C_\ell \propto \Omega_m^3 \sigma_8^8$$

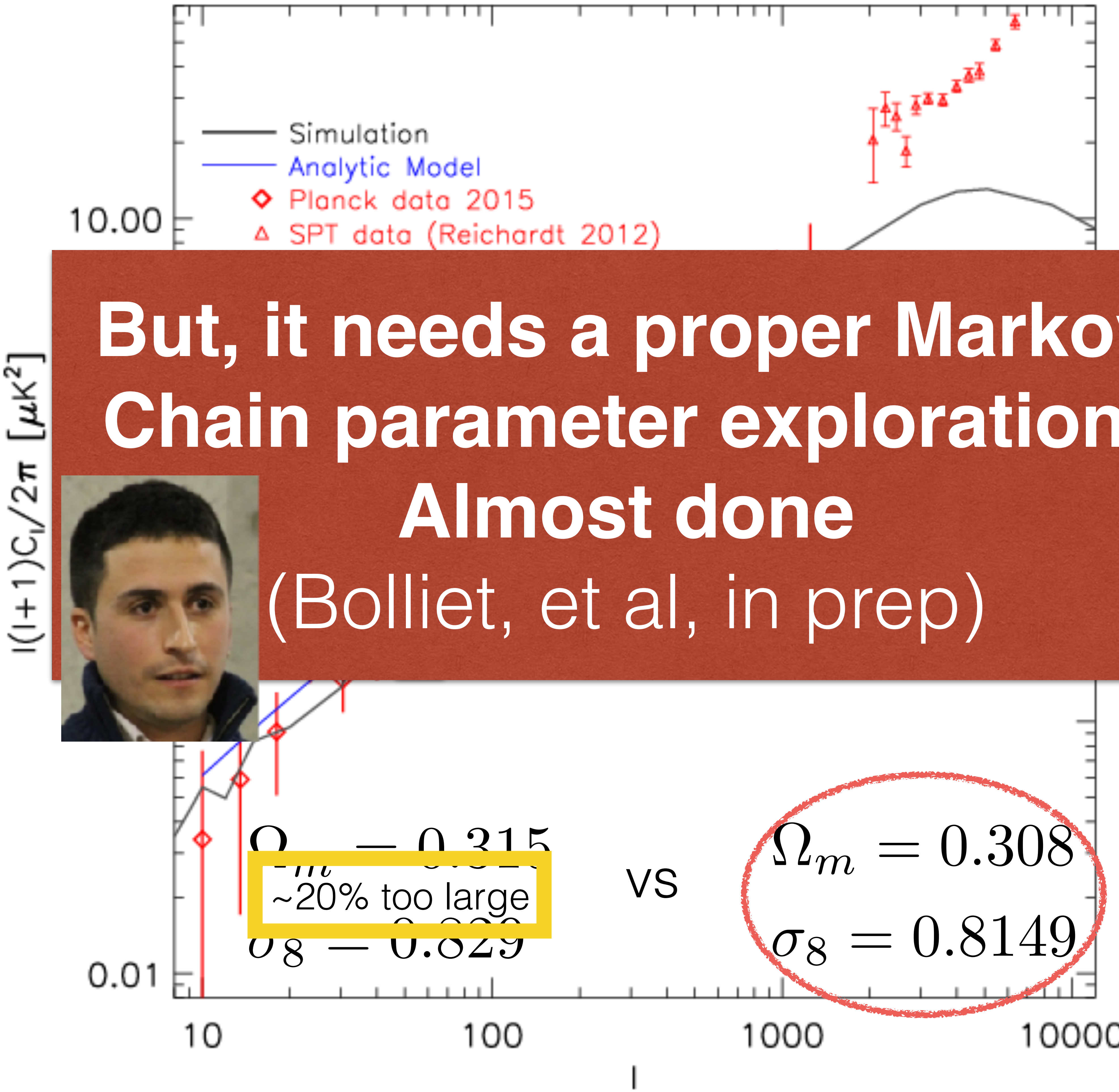
$\Omega_m = 0.315$ vs $\Omega_m = 0.308$

$\sigma_8 = 0.829$ vs $\sigma_8 = 0.8149$

Dolag, EK, Sunyaev (2016)



Dolag, EK, Sunyaev (2016)



But, it needs a proper Markov Chain parameter exploration. Almost done

(Bolliet, et al, in prep)

$\Omega_m = 0.315$

~20% too large

$\sigma_8 = 0.829$

vs

$\Omega_m = 0.308$

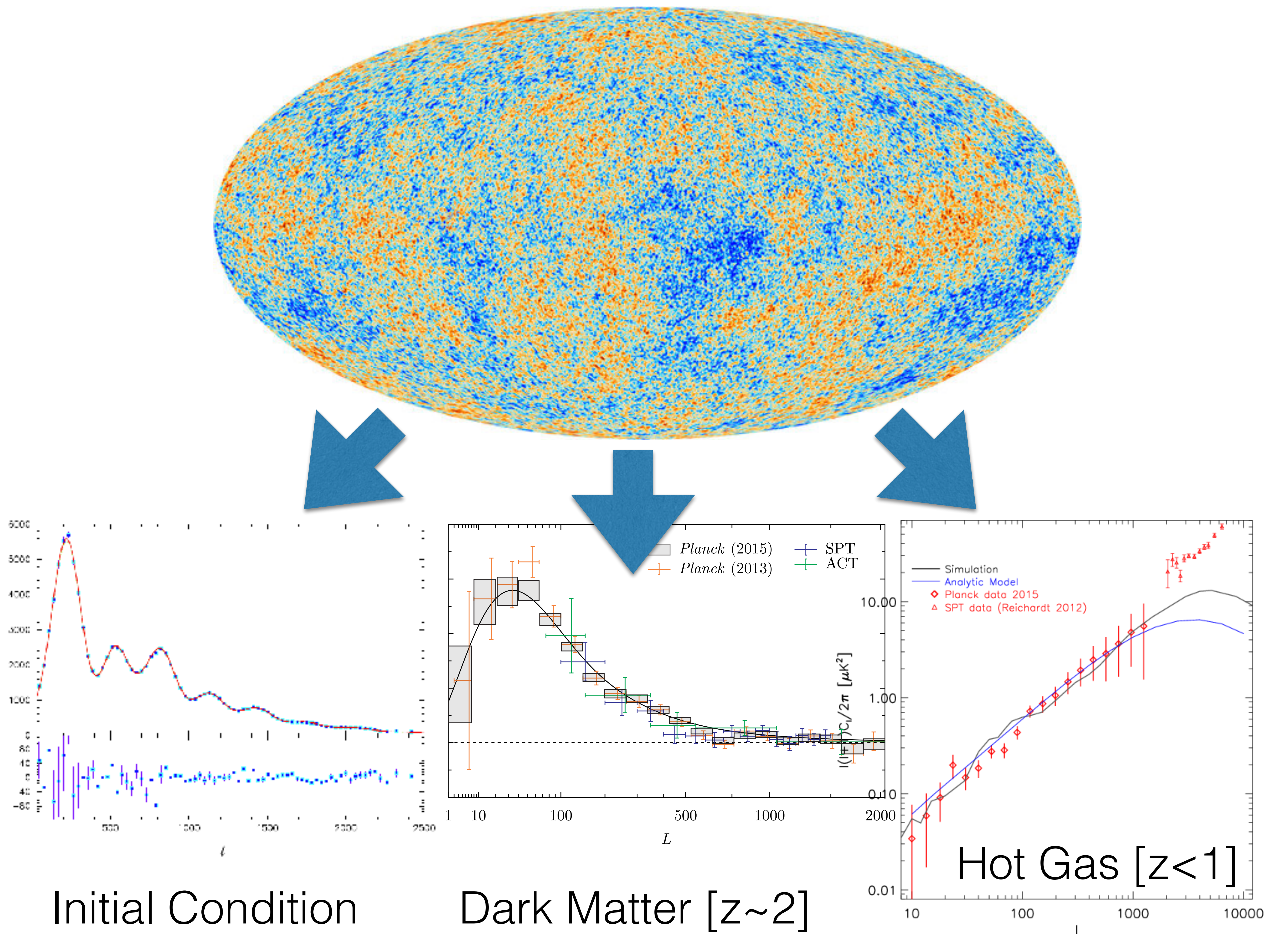
$\sigma_8 = 0.8149$

Codes (CRL)

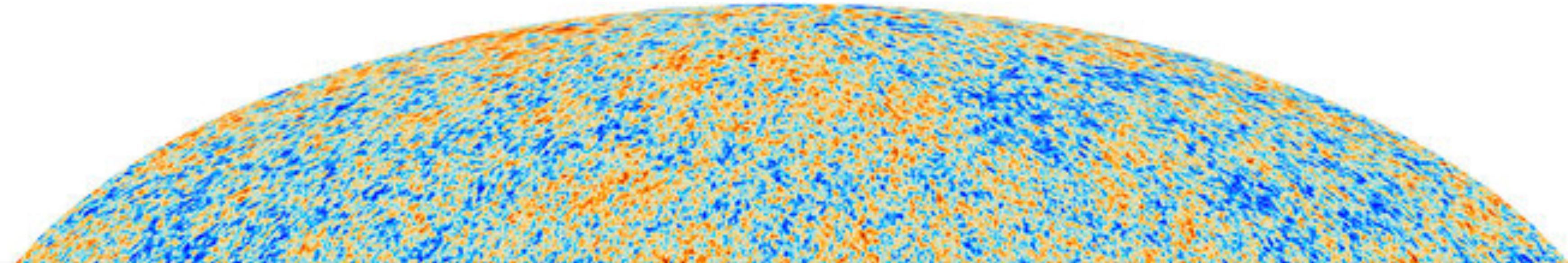
http://wwwmpa.mpa-garching.mpg.de/~komatsu/crl/

Clusters of Galaxies

- Converting Virial Mass to Overdensity Mass
- Gas Pressure and Sunyaev-Zel'dovich Effect Profiles (Arnaud et al.)
- Fourier Transform of the Sunyaev-Zel'dovich Effect Profile (Arnaud et al.)
- Power Spectrum of the Sunyaev-Zel'dovich Effect (Arnaud et al.)
- Gas Pressure and Sunyaev-Zel'dovich Effect Profiles (Komatsu-Seljak)
- Fourier Transform of the Sunyaev-Zel'dovich Effect Profile (Komatsu-Seljak)
- Power Spectrum of the Sunyaev-Zel'dovich Effect (Komatsu-Seljak)
- Power Spectrum of the Sunyaev-Zel'dovich Effect (Self-similar Arnaud et al., as in Shaw et al. 2010)
- Gas Pressure and Sunyaev-Zel'dovich Effect Profiles (Planck 2013)
- Power Spectrum of the Sunyaev-Zel'dovich Effect (Planck profile and parameters, as in Dolag et al. 2015)
- Mean Compton Y (Planck profile and parameters, as in Dolag et al. 2015)
- Gas Pressure and Sunyaev-Zel'dovich Effect Profiles (Battaglia et al.)
- Mean Compton Y (Battaglia et al. profile and WMAP9 parameters, as in Hill et al. 2015)
- Bin-integrated PDF of Compton Y (Planck profile and Magneticum parameters, as in Dolag et al. 2015)
- Electron density, X-ray temperature, and electron pressure profiles of Vikhlinin's low-z sample

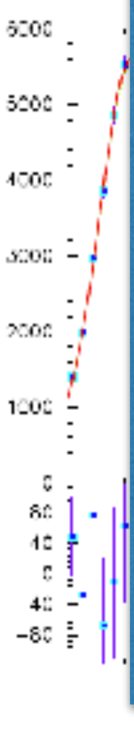


Planck (2015)
Planck (2013)
SPT
ACT
L
Simulation
Analytic Model
Planck data 2015
SPT data (Reichardt 2012)
l(l+1)C_l/2π [μK²]
Initial Condition
Dark Matter [z~2]
Hot Gas [z<1]



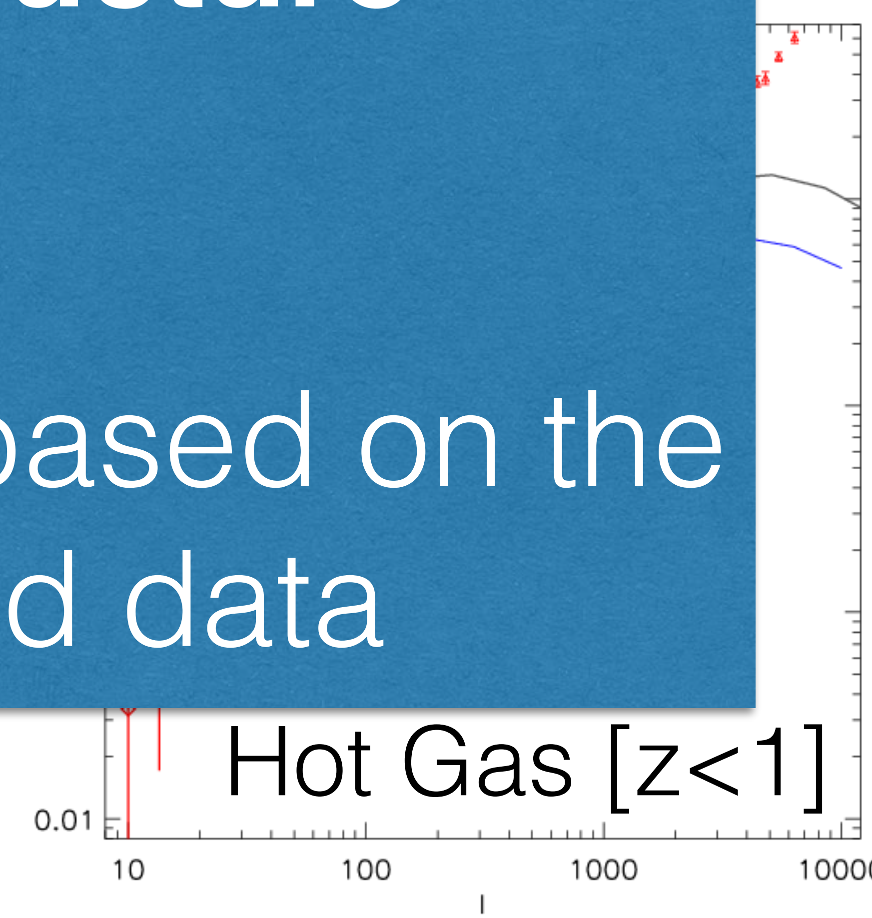
Standard ΛCDM Model, starting with **inflation** producing adiabatic, Gaussian, isotropic, $n_s<1$ primordial fluctuations fit all the data from the **initial condition to structure formation!**

These results are all solely based on the microwave background data



Initial Condition

Dark Matter [z~2]



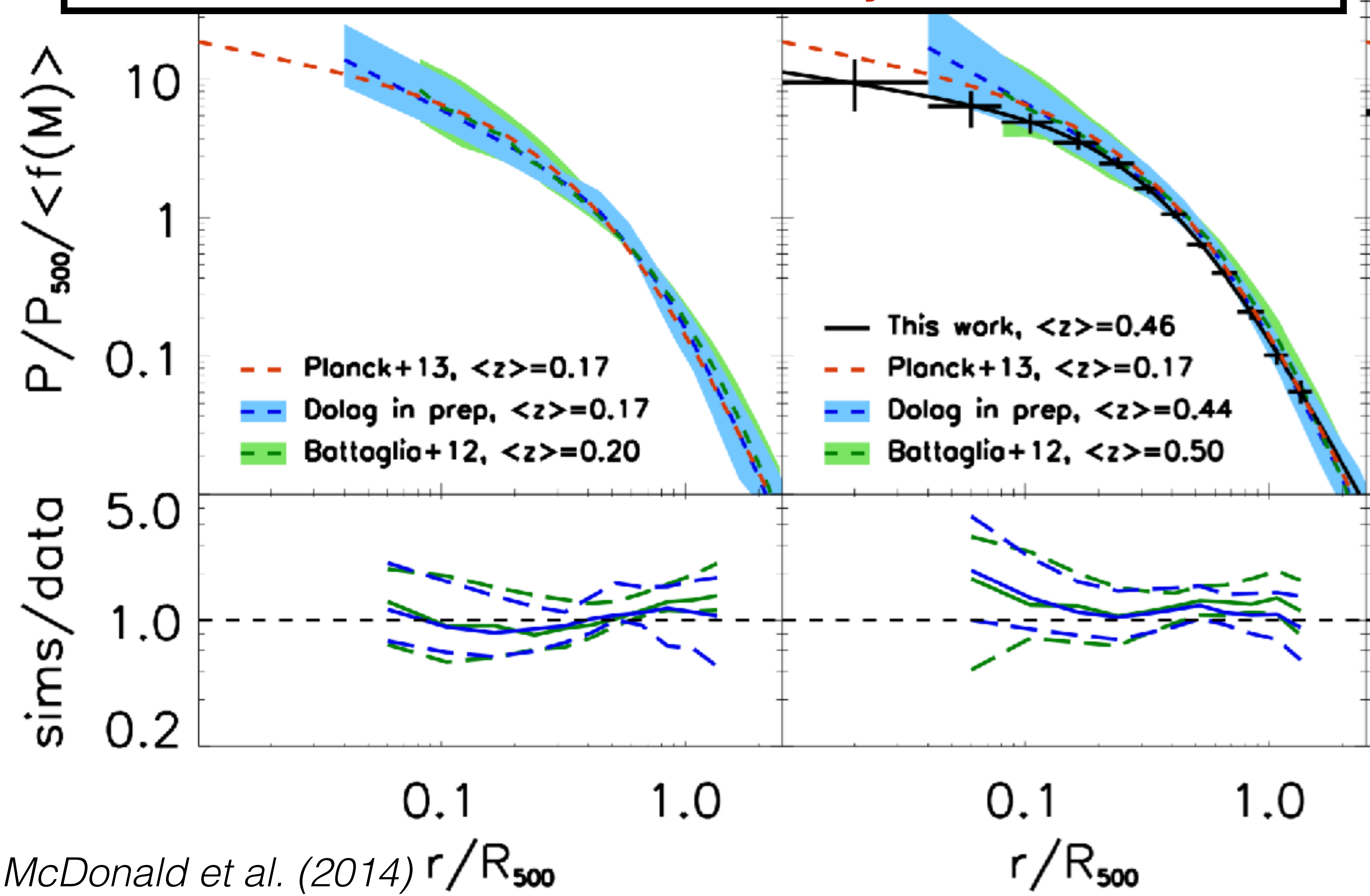
Hot Gas [z<1]

Toward more satisfaction

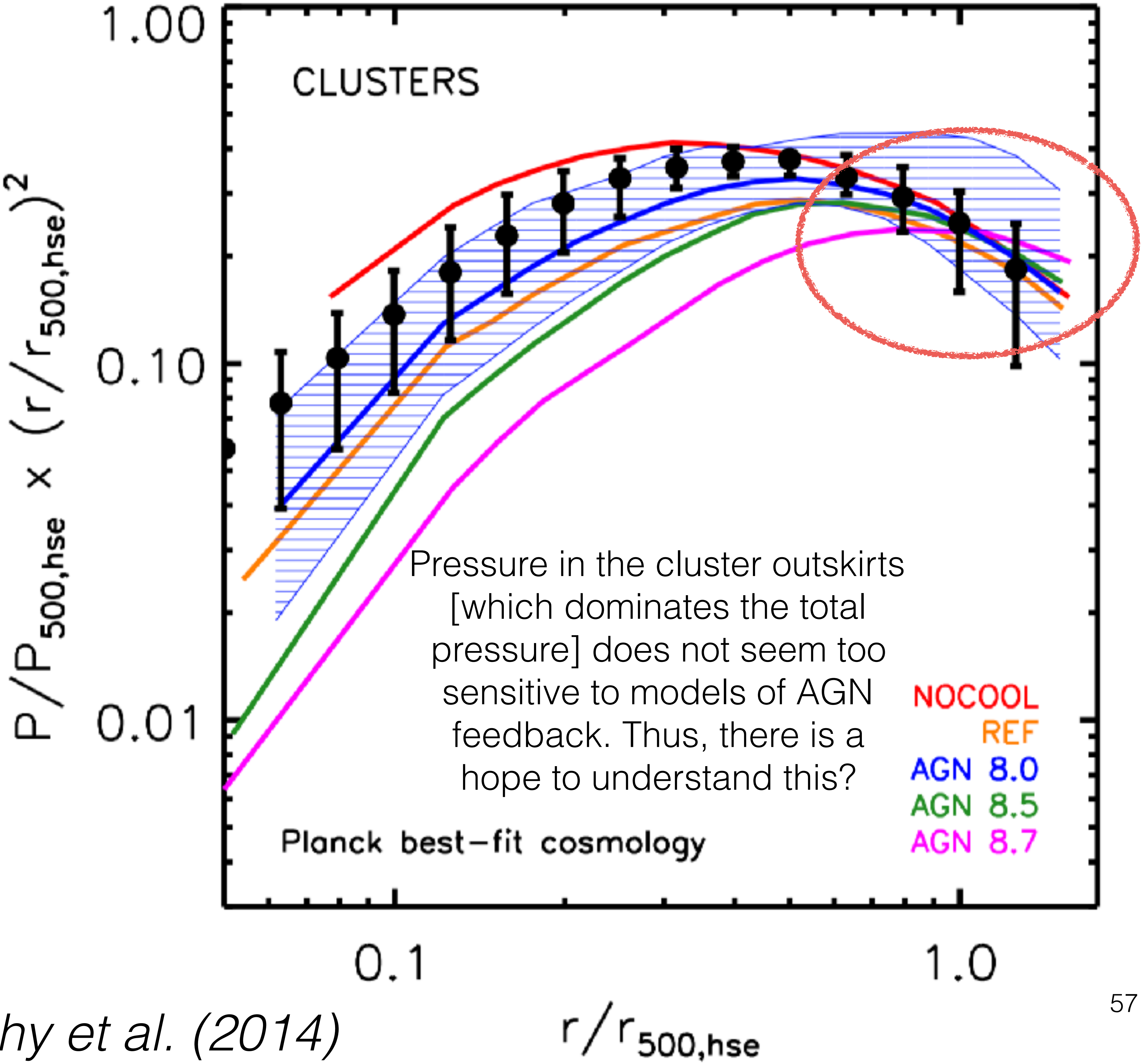
$$C_\ell = \int dz \frac{dV}{dz} \int dM \frac{dn}{dM} |y_\ell(M,z)|^2$$

- The key ingredient of the power spectrum is a profile of **thermal pressure of electrons**
- We can simulate this… but, it would be great to understand it physically before trusting our results on σ_8 from the SZ power spectrum on large scales

The pressure profiles in Dolag's simulations agree well with **those measured by Planck**



McDonald et al. (2014)



McCarthy et al. (2014)

Makino, Sasaki & Suto (1998); Komatsu & Seljak (2001)

Hydrostatic Equilibrium

$$\frac{1}{\rho_{\rm gas}(r)}\frac{\partial P_{\rm gas}(r)}{\partial r} = -\frac{GM(<r)}{r^2}$$

- We now know a lot about the matter distribution in galaxy clusters (i.e., NFW profile)
- **Why can't we just compute the gas pressure by balancing it against gravity of an NFW profile?**
- **We can.** But, **it will give you the total pressure, rather than thermal pressure**

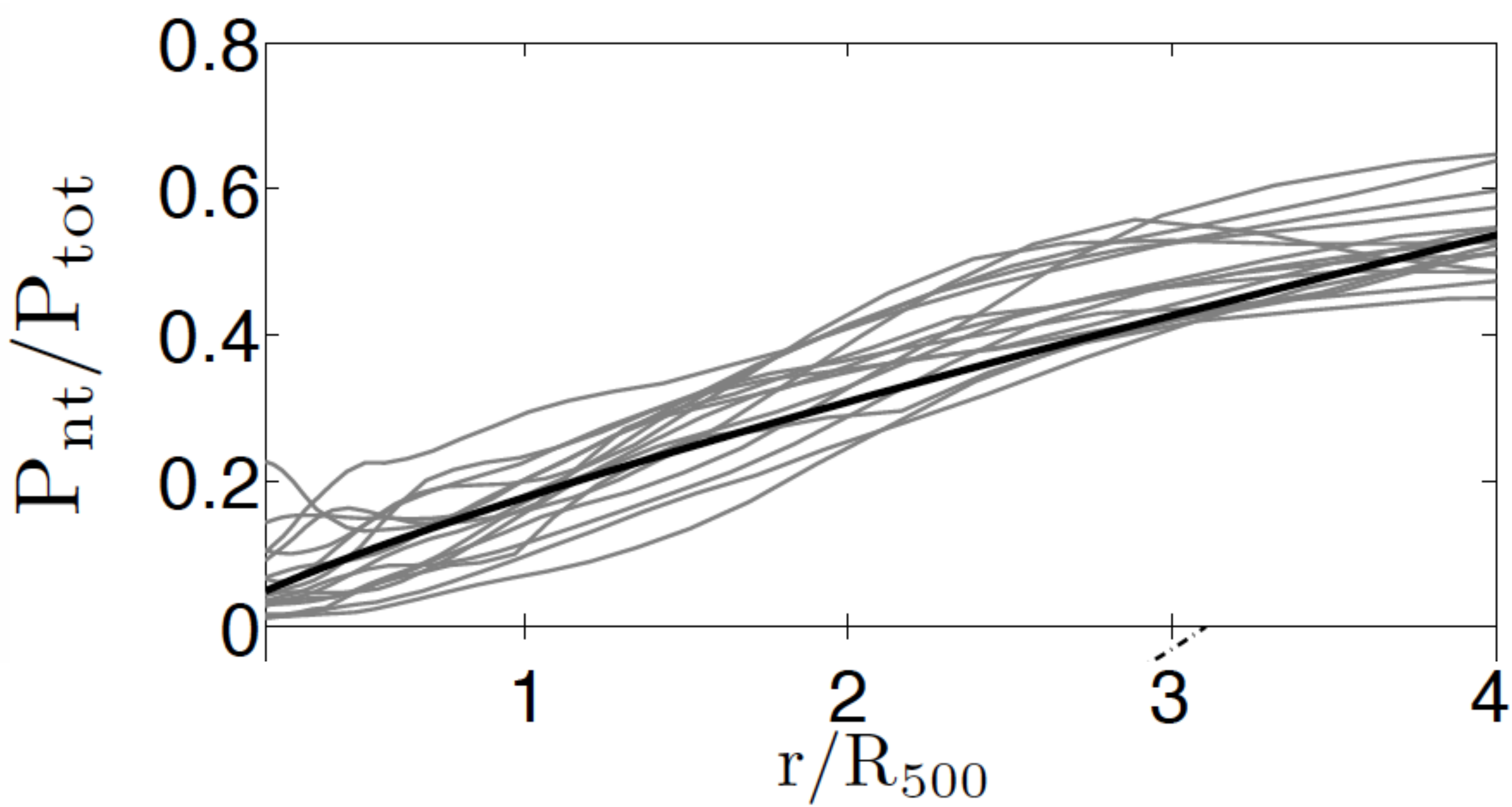
Non-thermal Pressure

- The HSE equation $$\frac{1}{\rho_{\rm gas}(r)}\frac{\partial P_{\rm gas}(r)}{\partial r} = -\frac{GM(<r)}{r^2}$$
  - includes the total pressure; however, not all kinetic energy of in-falling gas is thermalised
  - There is evidence that there is significant **non-thermal pressure support** coming from bulk motion of gas (e.g., turbulence)
- Therefore, the correct equation to use would be

$$\frac{1}{\rho_{\rm gas}(r)}\frac{\partial[P_{\rm th}(r) + P_{\rm non-th}(r)]}{\partial r} = -\frac{GM(<r)}{r^2}$$

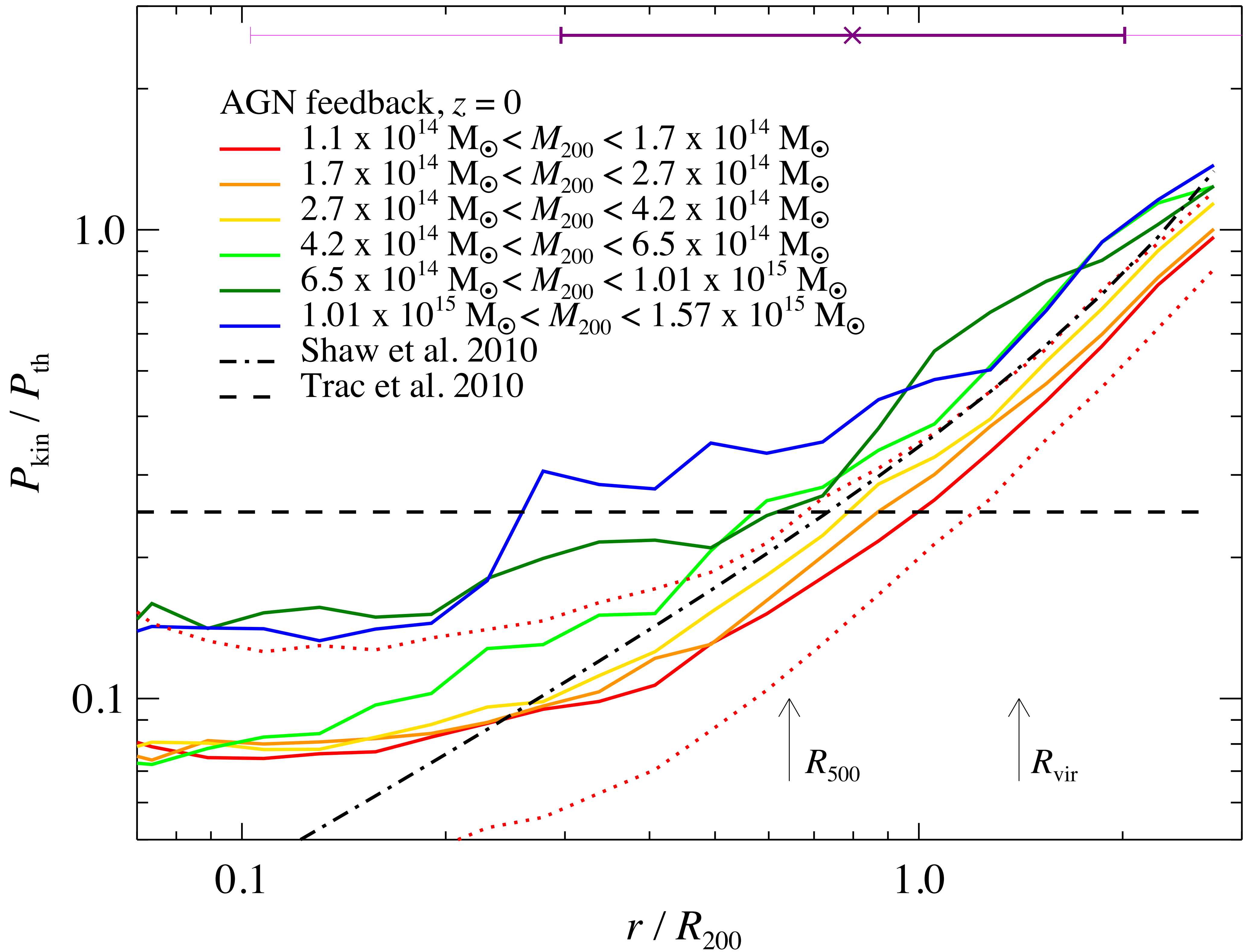
Not including $P_{\rm non\text{-}th}$ leads to overestimation of the thermal pressure!

Shaw, Nagai, Bhattacharya & Lau (2010)



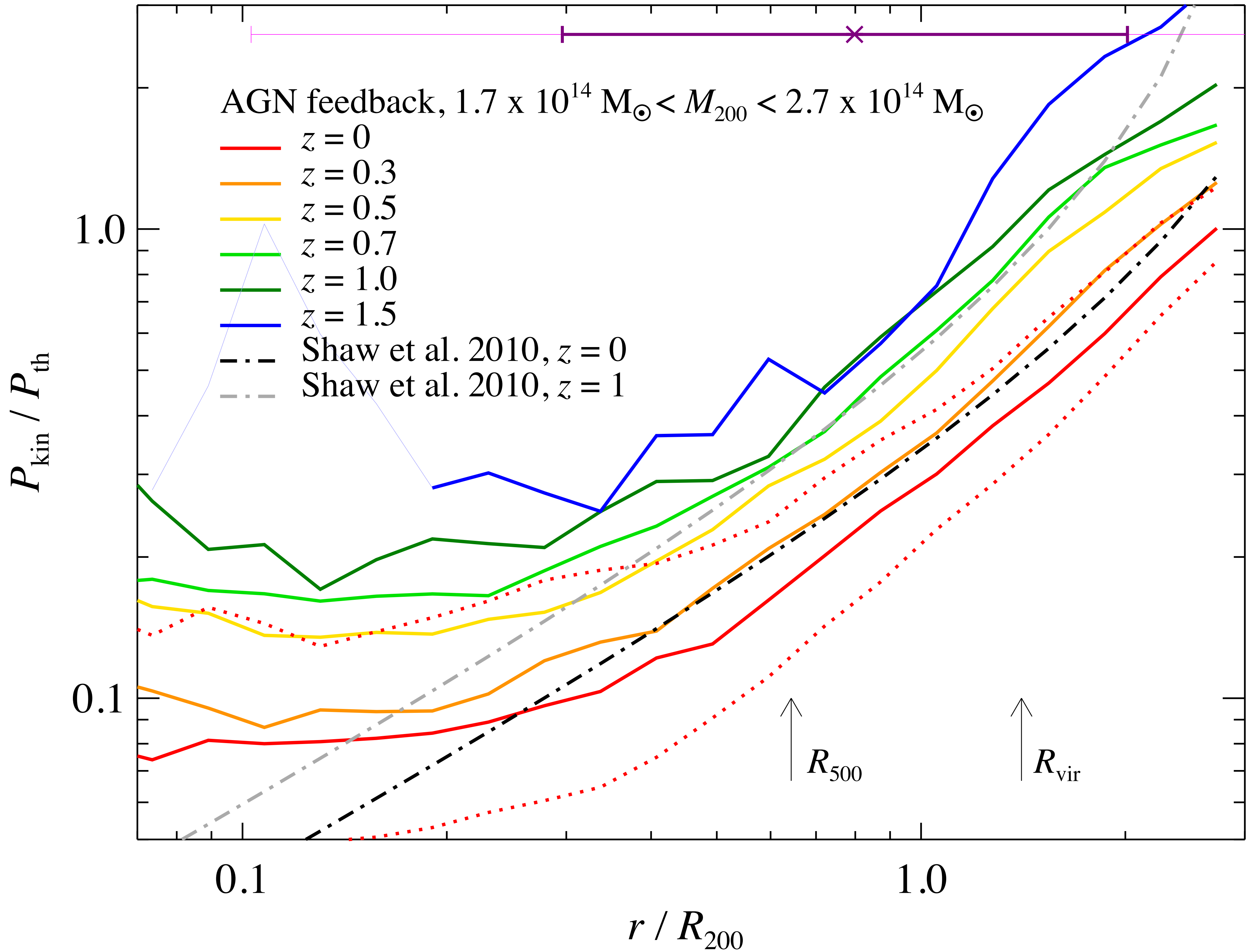
- Simulations by Shaw et al. show that the non-thermal pressure [by bulk motion of gas] divided by the total pressure increases toward large radii. But why?

Battaglia, Bond, Pfrommer & Sievers (2012)



- Battaglia et al.'s simulations show that the ratio increases for larger masses, and…

Battaglia, Bond, Pfrommer & Sievers (2012)



- …increases for larger redshifts. But why?

Analytical Model for Non-Thermal Pressure

- **Basic idea 1**: non-thermal motion of gas in clusters is sourced by the mass growth of clusters [via mergers and mass accretion] with efficiency η

- **Basic idea 2**: induced non-thermal motion decays and thermalises in a dynamical time scale

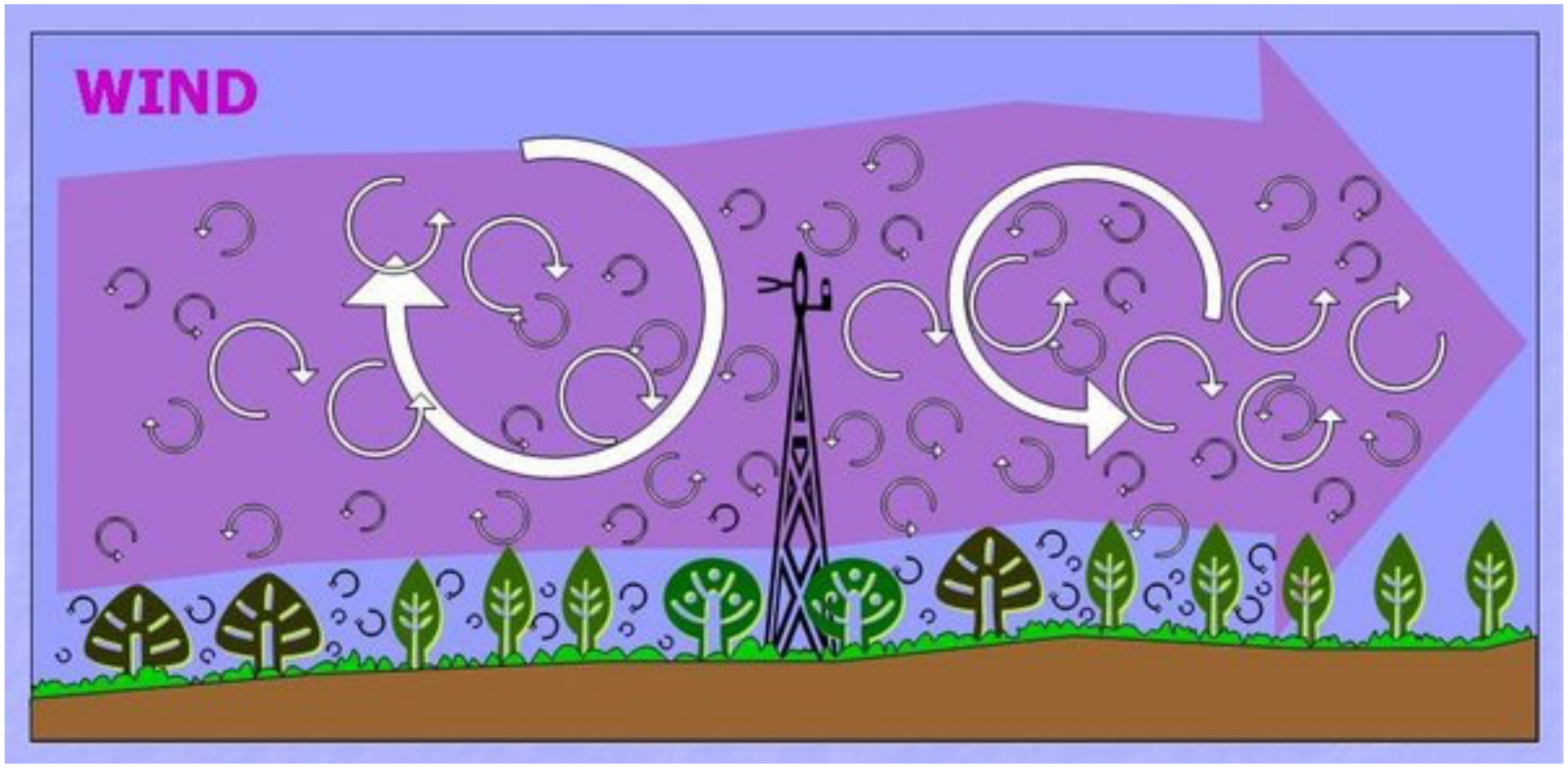
- Putting these ideas into a differential equation:

$$\frac{\mathrm{d}\sigma^2_{\mathrm{nth}}}{\mathrm{d}t} = -\frac{\sigma^2_{\mathrm{nth}}}{t_{\mathrm{d}}} + \eta\,\frac{\mathrm{d}\sigma^2_{\mathrm{tot}}}{\mathrm{d}t}$$

[$\sigma^2 = P/\rho_{gas}$]

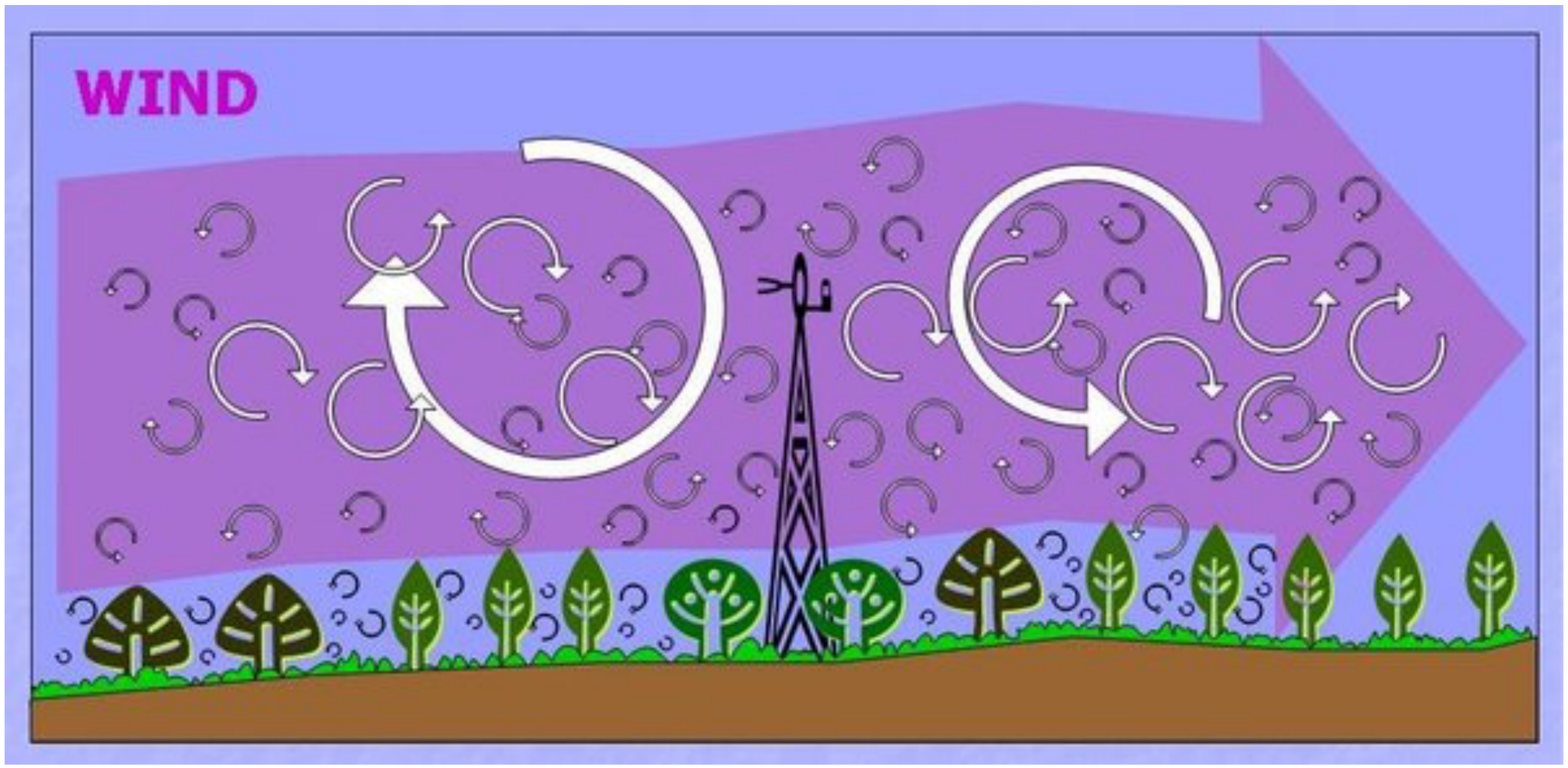
Shi & Komatsu (2014)

Finding the decay time, t_d



- Think of non-thermal motion as turbulence
- Turbulence consists of “eddies” with different sizes

Finding the decay time, t_d



- Largest eddies carry the largest energy

- Large eddies are unstable. They break up into smaller eddies, and transfer energy from large-scales to small-scales

Finding the decay time, t_d

- Assumption: the size of the largest eddies at a radius r from the centre of a cluster is proportional to r

- Typical peculiar velocity of turbulence is

$$v(r) = r\Omega(r) = \sqrt{\frac{GM(<r)}{r}}$$

- Breaking up of eddies occurs at the time scale of

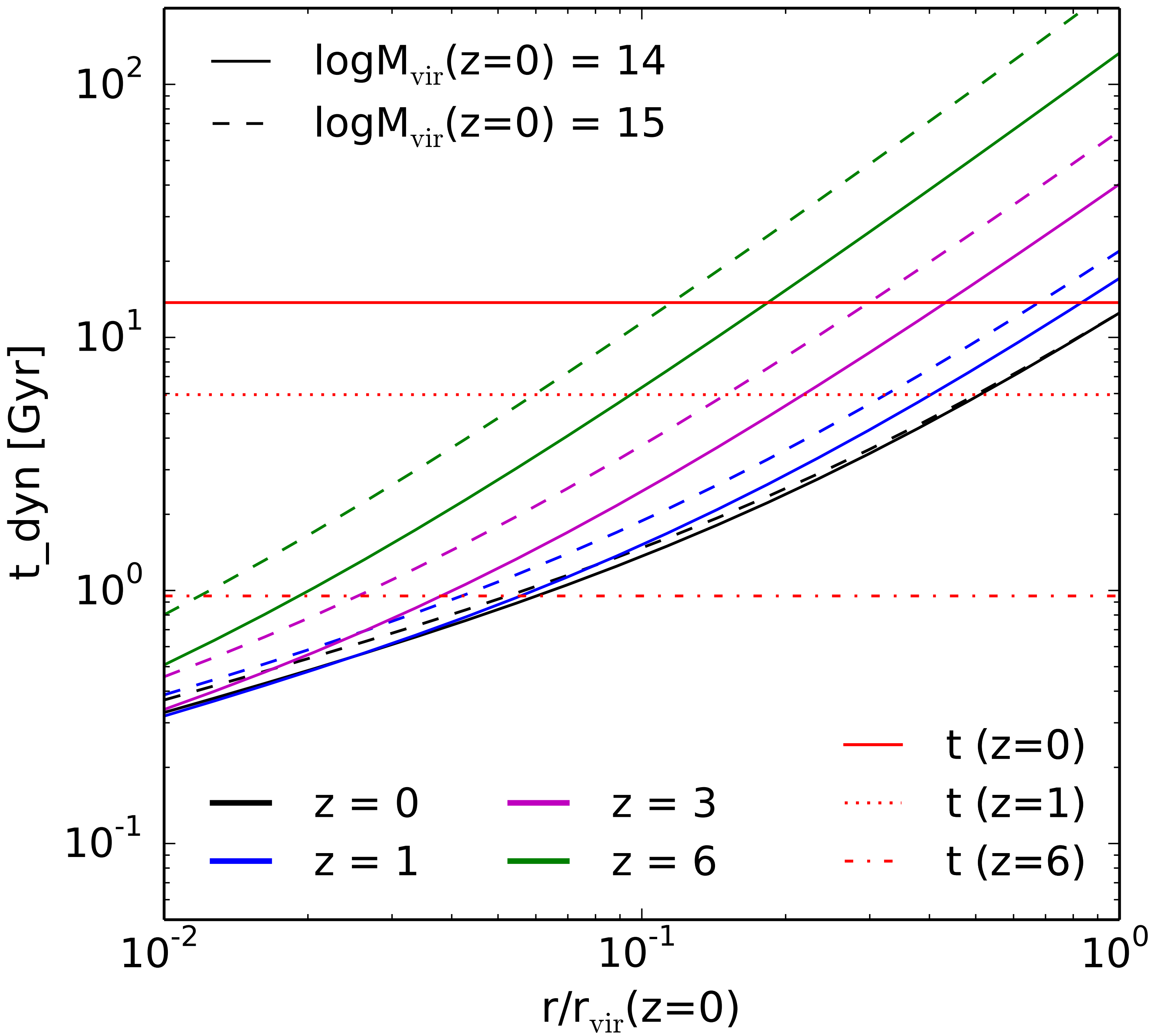
$$t_d \approx \frac{2\pi}{\Omega(r)} \equiv t_{dynamical}$$

- We thus write:

$$t_d \equiv \frac{\beta}{2} t_{dynamical}$$

Shi & Komatsu (2014)

Dynamical Time



- Dynamical time increases toward large radii. **Non-thermal motion decays into heat faster in the inner region**

Source term

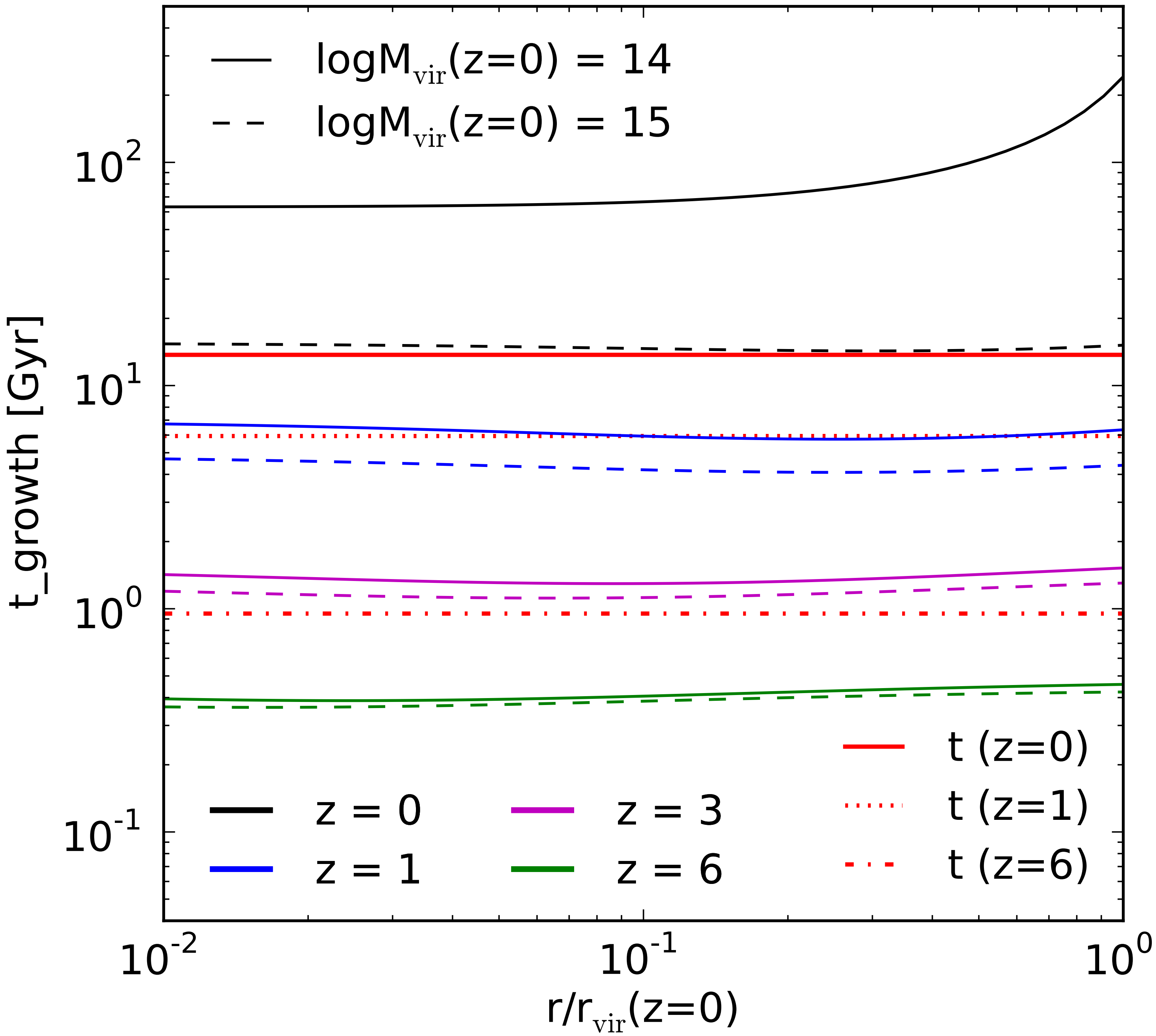
$$\frac{d\sigma^2_{nth}}{dt} = -\frac{\sigma^2_{nth}}{t_d} + \eta\,\frac{d\sigma^2_{tot}}{dt}$$

- Define the “growth time” as

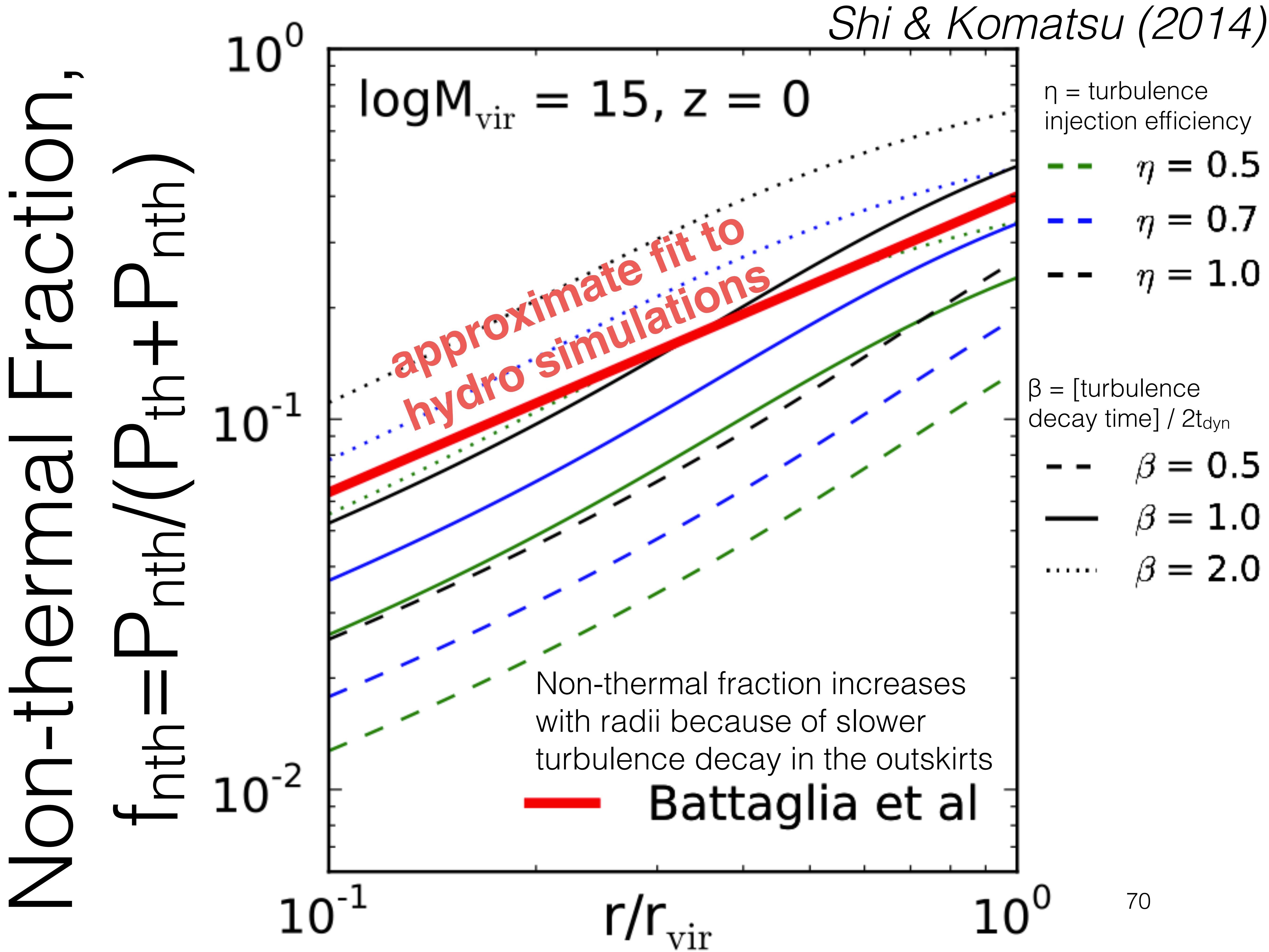
$$t_{growth} \equiv \sigma^2_{tot}\left(\frac{d\sigma^2_{tot}}{dt}\right)^{-1}$$

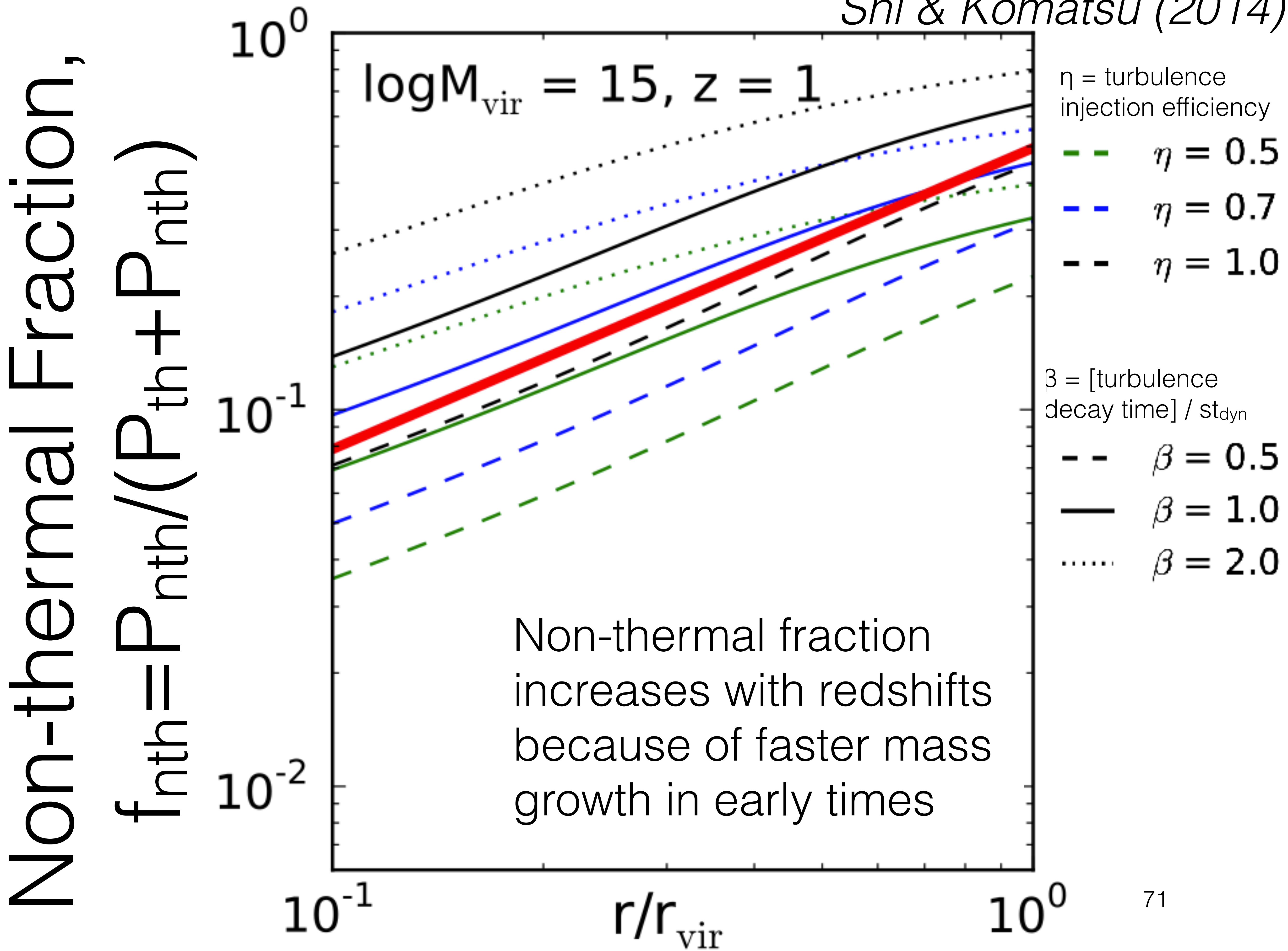
Shi & Komatsu (2014)

Growth Time



- Growth time increases toward lower redshifts and smaller masses. **Non-thermal motion is injected more efficiently at high redshifts and for large-mass halos**

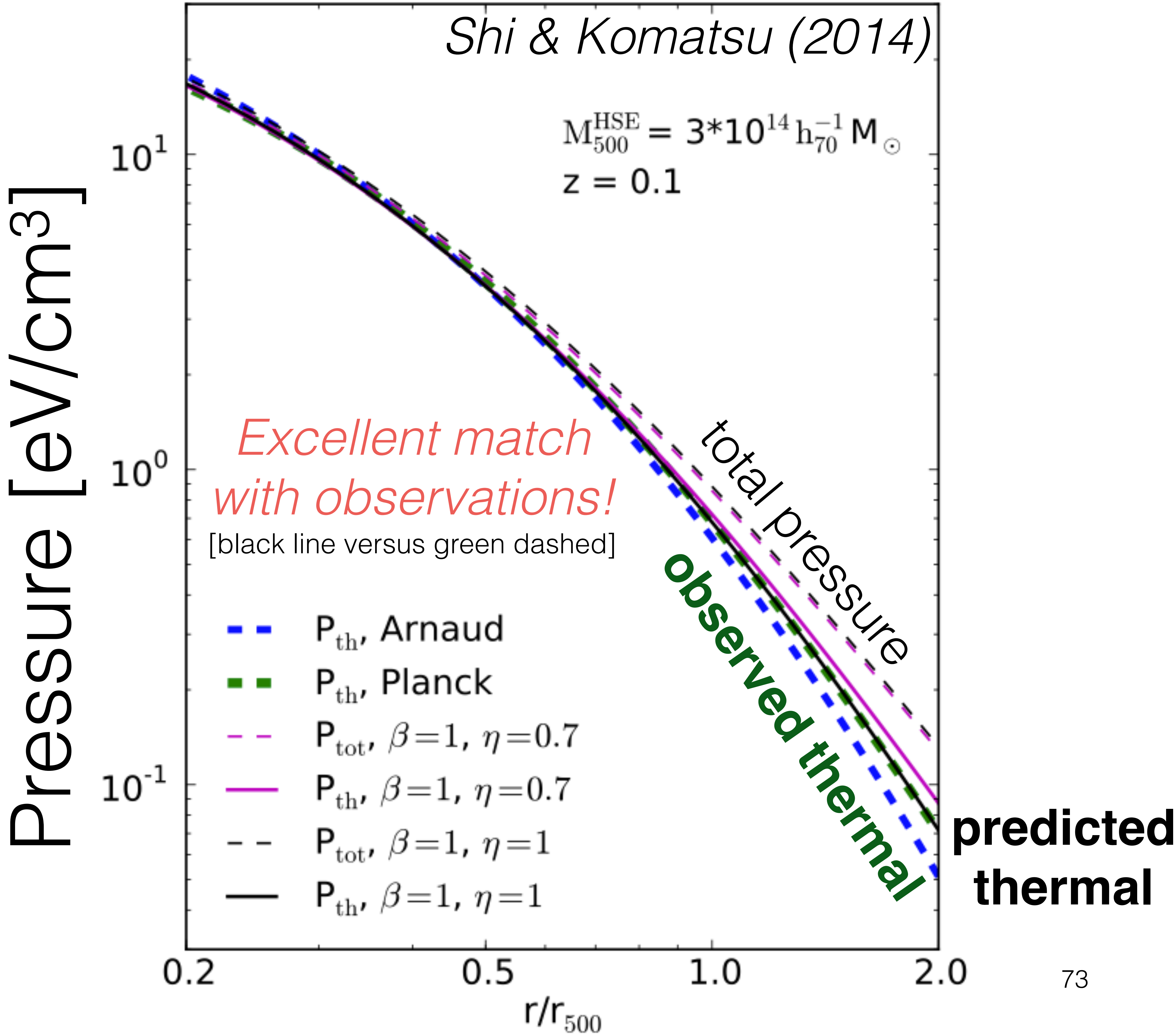

Shi & Komatsu (2014)
Non-thermal Fraction,
$f_{nth}=P_{nth}/(P_{th}+P_{nth})$
logM$_{vir}$ = 15, z = 0
approximate fit to hydro simulations
Non-thermal fraction increases with radii because of slower turbulence decay in the outskirts
Battaglia et al
η = turbulence injection efficiency
$\eta = 0.5$
$\eta = 0.7$
$\eta = 1.0$
β = [turbulence decay time] / 2t$_{dyn}$
$\beta = 0.5$
$\beta = 1.0$
$\beta = 2.0$
10^0
10^{-1}
10^{-2}
10^{-1}
r/r_{vir}
10^0


Non-thermal Fraction,
fnth=Pnth/(Pth+Pnth)
10^0
10^-1
10^-2
logMvir = 15, z = 1
r/rvir
10^-1
10^0
η = turbulence
injection efficiency
η = 0.5
η = 0.7
η = 1.0
β = [turbulence
decay time] / stdyn
β = 0.5
β = 1.0
β = 2.0
Non-thermal fraction
increases with redshifts
because of faster mass
growth in early times

With $P_{\text{non-thermal}}$ computed

- We can now predict the X-ray and SZ observables, by subtracting $P_{\text{non-thermal}}$ from P_{total}, which is fixed by the total mass

- We can then predict what the bias in the mass estimation if hydrostatic equilibrium with thermal pressure is used



Shi & Komatsu (2014)
$M_{500}^{HSE} = 3*10^{14} h_{70}^{-1} M_\odot$
z = 0.1
Excellent match
with observations!
[black line versus green dashed]
total pressure
observed thermal
predicted
thermal
P_{th}, Arnaud
P_{th}, Planck
P_{tot}, $\beta=1$, $\eta=0.7$
P_{th}, $\beta=1$, $\eta=0.7$
P_{tot}, $\beta=1$, $\eta=1$
P_{th}, $\beta=1$, $\eta=1$
Pressure [eV/cm³]
10^1
10^0
10^{-1}
0.2
0.5
1.0
2.0
r/r_{500}

Summary

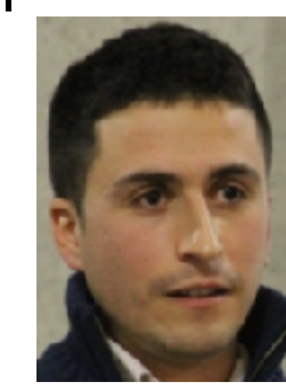
- New results on the SZ effect, *from small to large:*


T. Kitayama

1. The first SZ image by ALMA - opening up a new study of cluster astrophysics via pressure fluctuations


K. Dolag

2. The SZ power spectrum at l<1000 has been determined finally! **Next: to get σ_8 out of it**


B. Bolliet


X. Shi

3. We now understand, *quantitatively*, the origin and distribution of non-thermal pressure in cluster outskirts

Compton Y Map of RXJ1347–1145

<u>on-source integration times</u>

5.6 hours with 7-m array

2.6 hours with 12-m array

Thank you TAC!